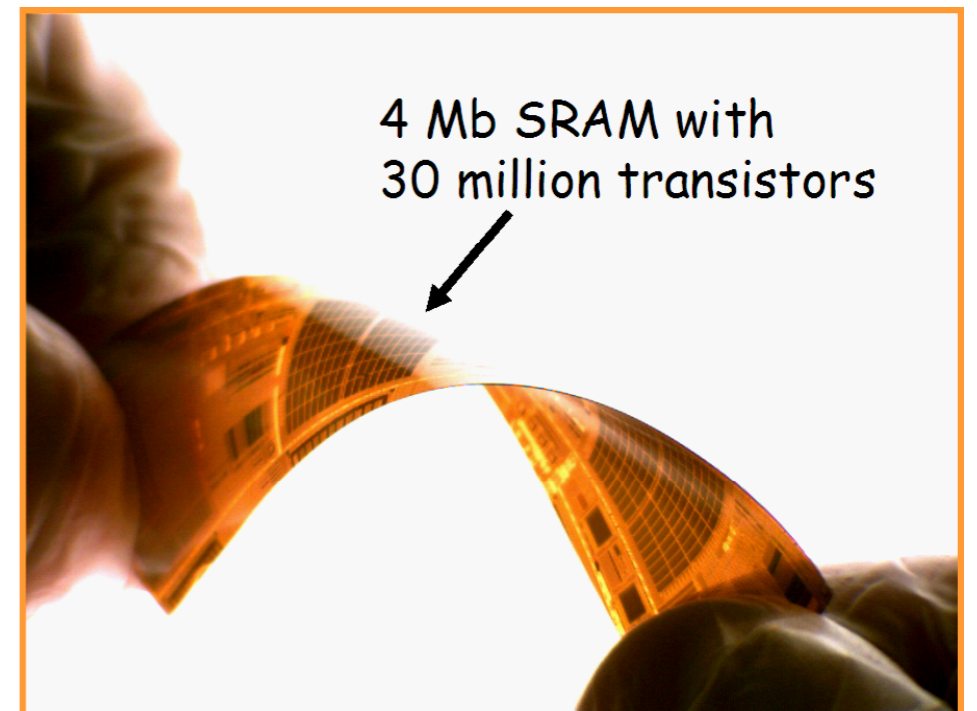


Low Mass (high rate, high resolution) Tracking

Ronald Lipton, Fermilab; Jack Ritchie U. Texas at Austin
Project X Workshop

Experimental Landscape
Gas tracking experiments
Silicon Tracking experiments
Future R&D



SOI thinned to 6 micon and bonded
to 3 mil kapton (MIT-LL)

The Experimental Landscape

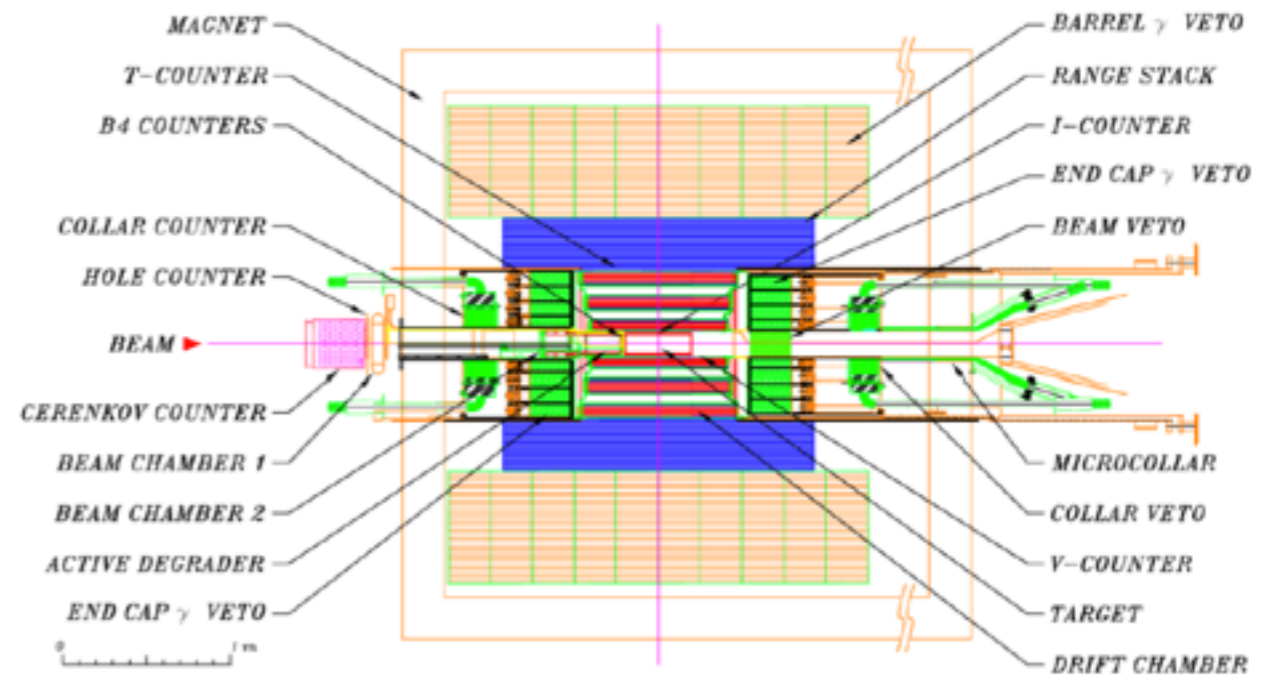
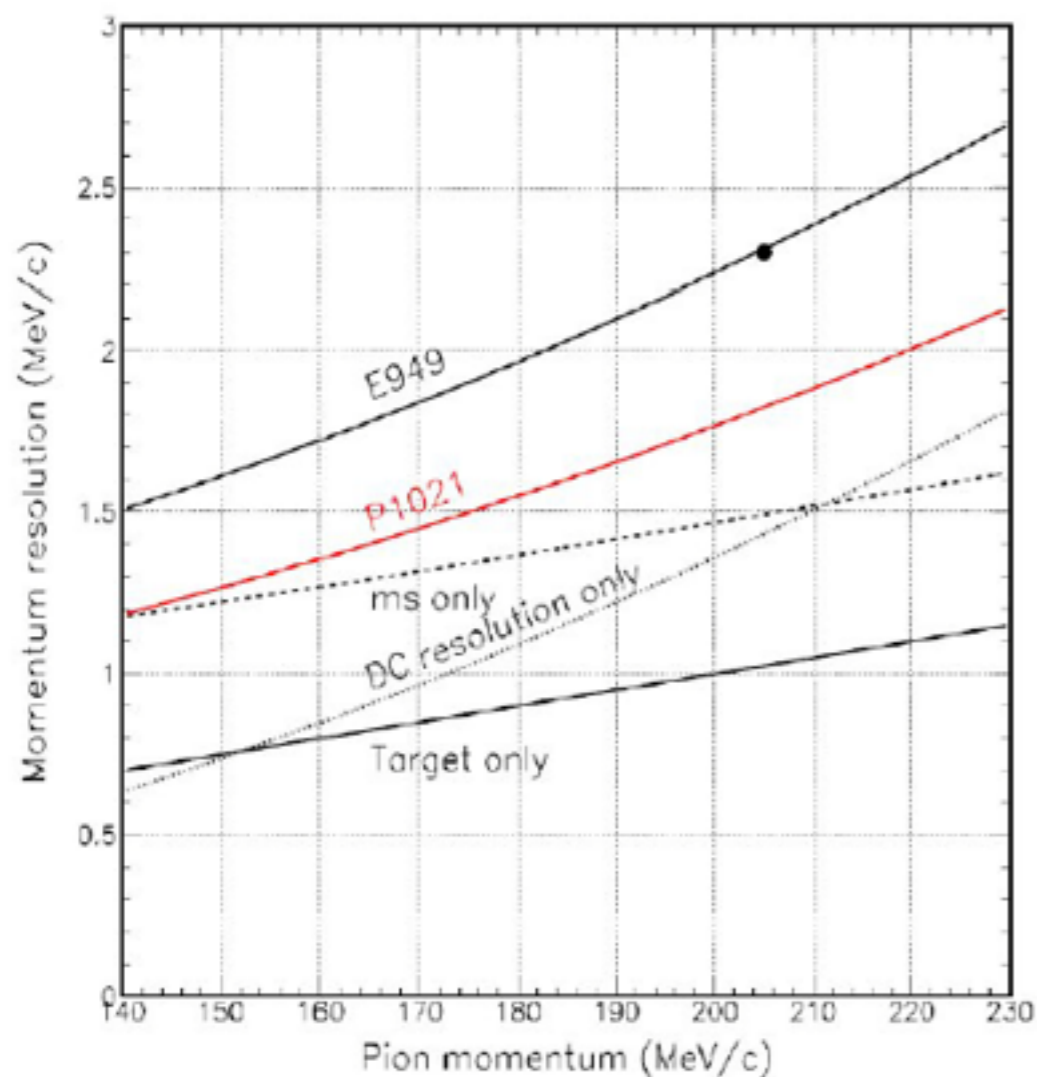
- Experiments designed to study rare events require:
 - Mhz to Ghz/cm² rates in the tracking systems
 - 1 ns - 10's psec time resolution to reduce accidental rates
 - $\ll 1\%$ radiation length/hit to reduce material induced multiple scattering or backgrounds
 - Radiation resistance?
 - Good position (mass) resolution
- We went over some examples (ORKA, G-2, $\mu \rightarrow e$ conversion, $\mu \rightarrow e \gamma$, nn-bar oscillations)
- Each is unique with some clear and some not-so-clear tradeoffs

Can extract some general R&D needs - but specific requirements need detailed analysis of proposed experiments

ORKA $k^+ \rightarrow \pi^+ \nu \nu$ (Numao)

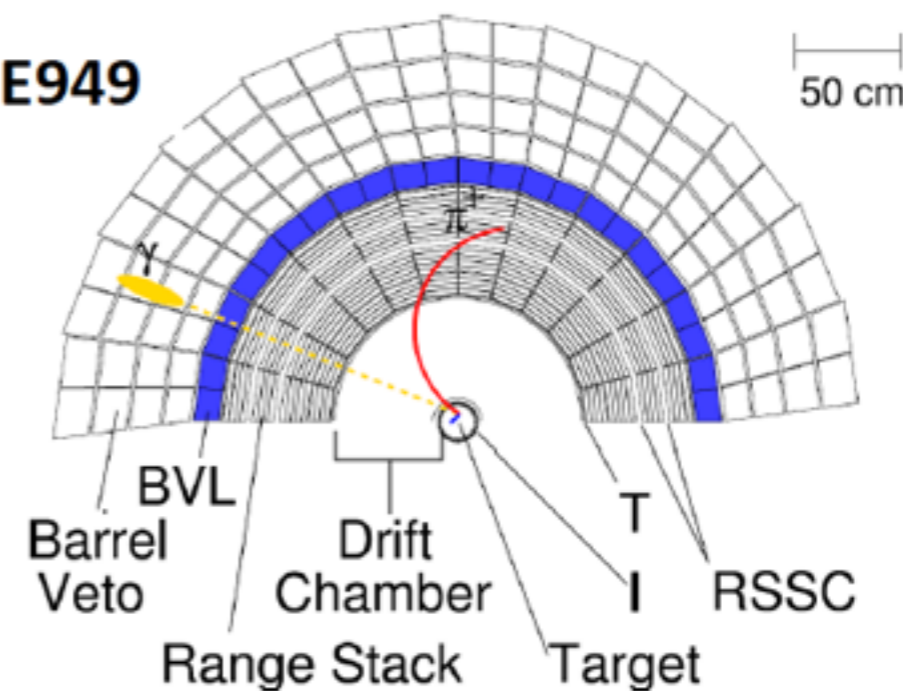
Momentum resolution is key to background rejection

- Energy loss in target, multiple scattering, drift chamber resolution



End view

E949



E949 chamber Total

Foils	4 middle foils	0.4×10^{-3}
Wires	3 x 4 cathode planes	0.2×10^{-3}
	4 x 4 anode planes	0.2×10^{-3}
Gas	15 cm Ar/Ethan	0.9×10^{-3}
	16 cm N2	0.4×10^{-3}

Possible ORCA Improvements from E949

Improvements toward ORKA

Better resolution beyond the higher B-field effect?

- Longer path length?

Larger OD possible?

- He based gas to reduce MS?

(Very small improvement by filling the N2 layers with He).

- Smaller/hexagonal cells? Thinner super-layers → less Ar.
- GEM or Si-strip detectors at inner/outer radius?

Numao

Many incremental gains
- need to quantify

What are the areas to
provide most benefit?
Do inner/outer high
precision detectors help
significantly?

Is there a better way to
achieve z resolution in
a large chamber?

Higher rates

- Cathode shaping time is too long.

Also, AC coupled → DC coupled? Record waveform?

- Thinner cathode strips to match the cell size?

Better s/n ratio?

Longer Chamber

- Z-resolution ok? Wire stability? Foil angle? Attenuation?

Photon veto

- Active end plates? Mixing active material in the endcap?

G-2 (Casey, Nguyen)

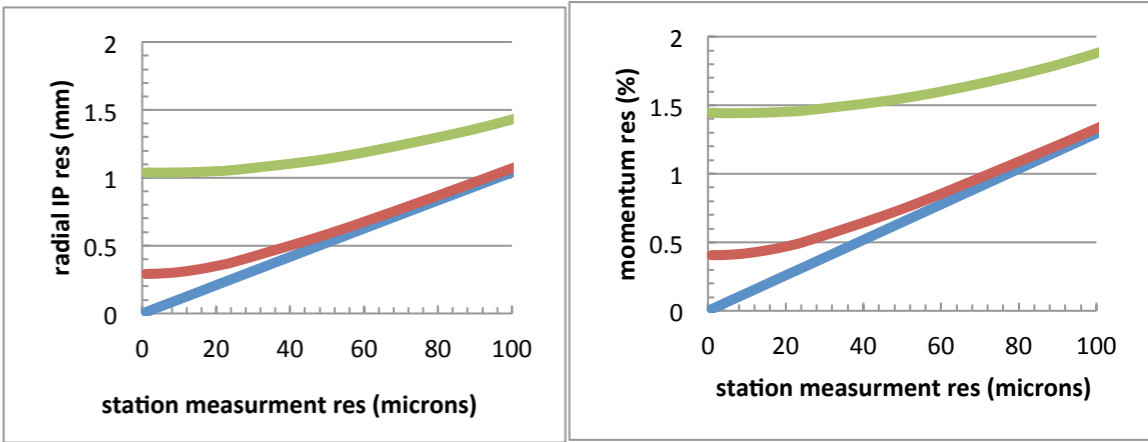
Systematic uncertainty	E821 final	Projected	Role played by tracking detector
Magnetic field map and beam profile	0.03 ppm	0.03 ppm	Measure beam profile on a fill by fill basis ensuring proper alignment
E-field and pitch correction	0.05 ppm	0.03 ppm	Measure first and second moments of beam profile in radial and vertical direction
Pileup correction	0.08 ppm	0.04 ppm	Isolate an event library with more than one positron hitting the calorimeter
Calorimeter gain stability	0.12 ppm	0.02 ppm	Better tracking resolution and E/p measurements.

Have considered

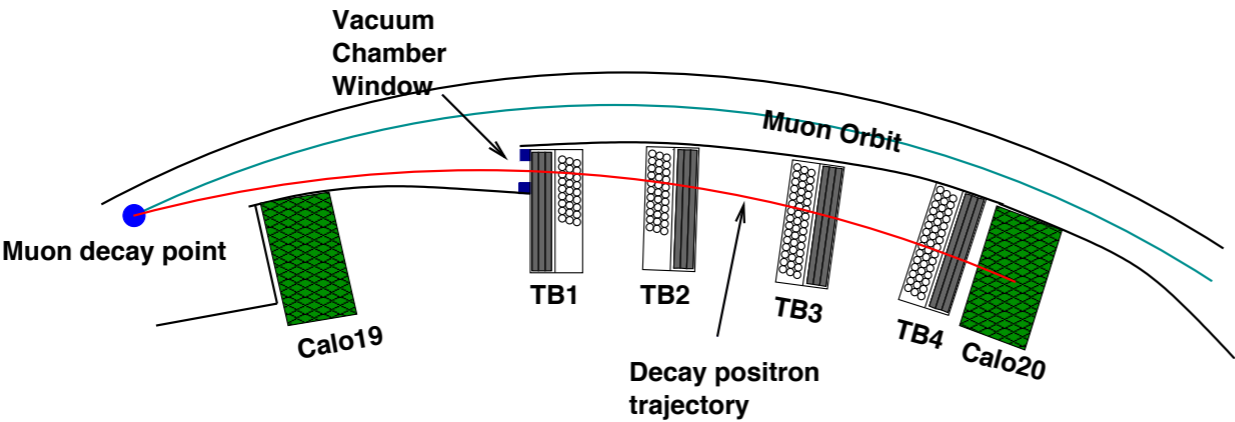
300 μ Si strips, 150 μ Si strips, 50 μ Si pixels, fibers, wire chambers, straw doublets, triplets, quadruplets, XY, UV at various angles

Bottom line

UV straws win: adequate resolution in radial and vertical, good vacuum properties, large coverage, room for redundancy....

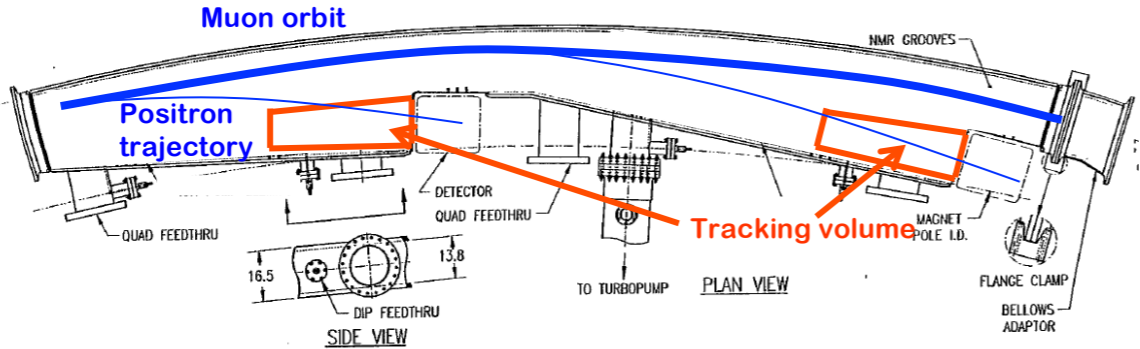


E821

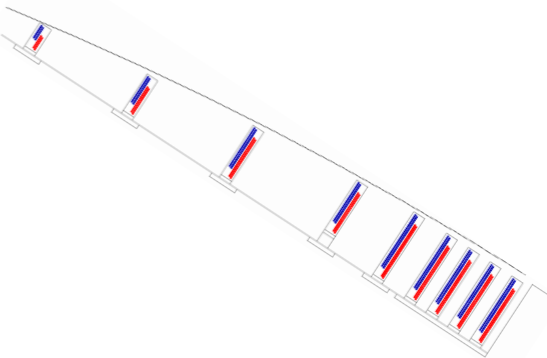


- Vacuum chamber modified in front of one calo
 - Drastically effected positrons hitting calo
 - Drives need to put new system in vacuum
- Chamber locations not optimal
 - Only accepted highest energy positrons
- Sufficient resolution to meet physics requirements in the vertical plane
 - Best EDM limit
- Insufficient resolution to meet physics requirements in the radial (bending) plane
 - Can be resolved with better design, particularly better momentum acceptance

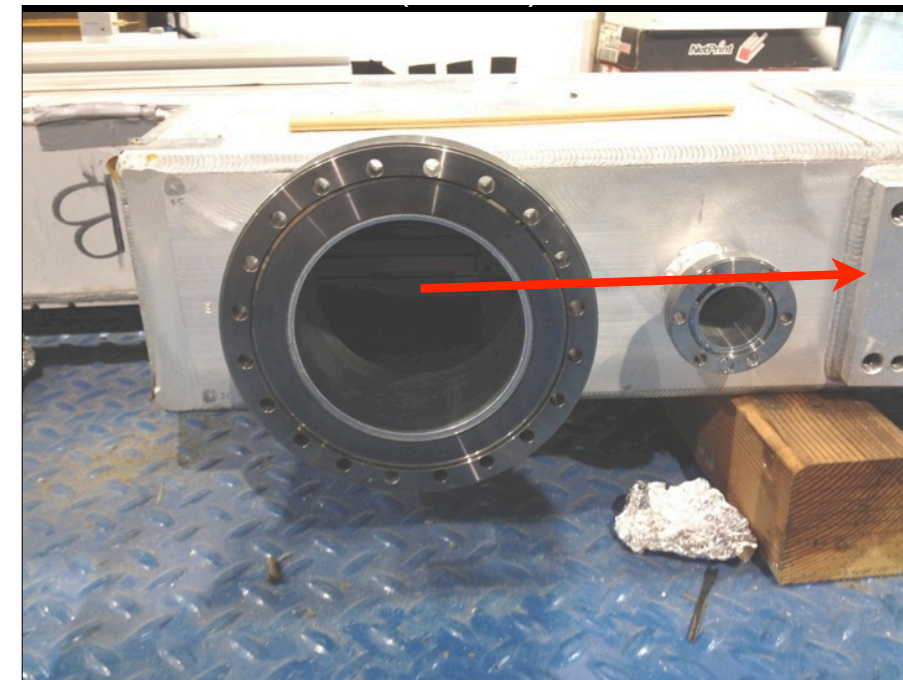
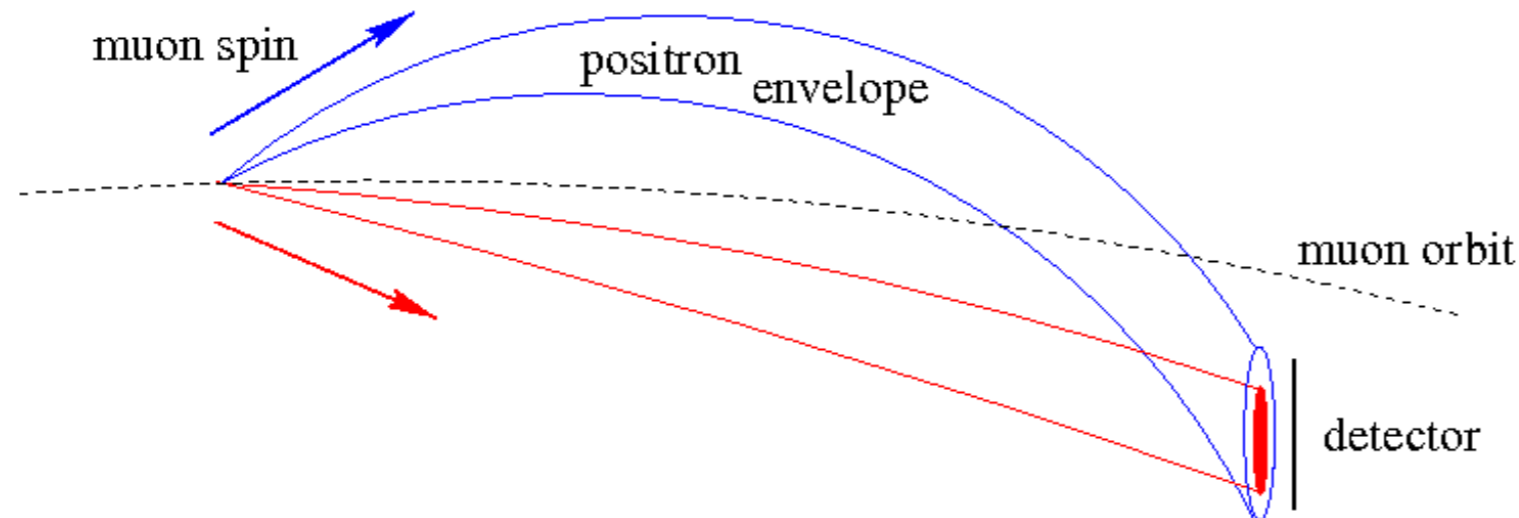
G-2



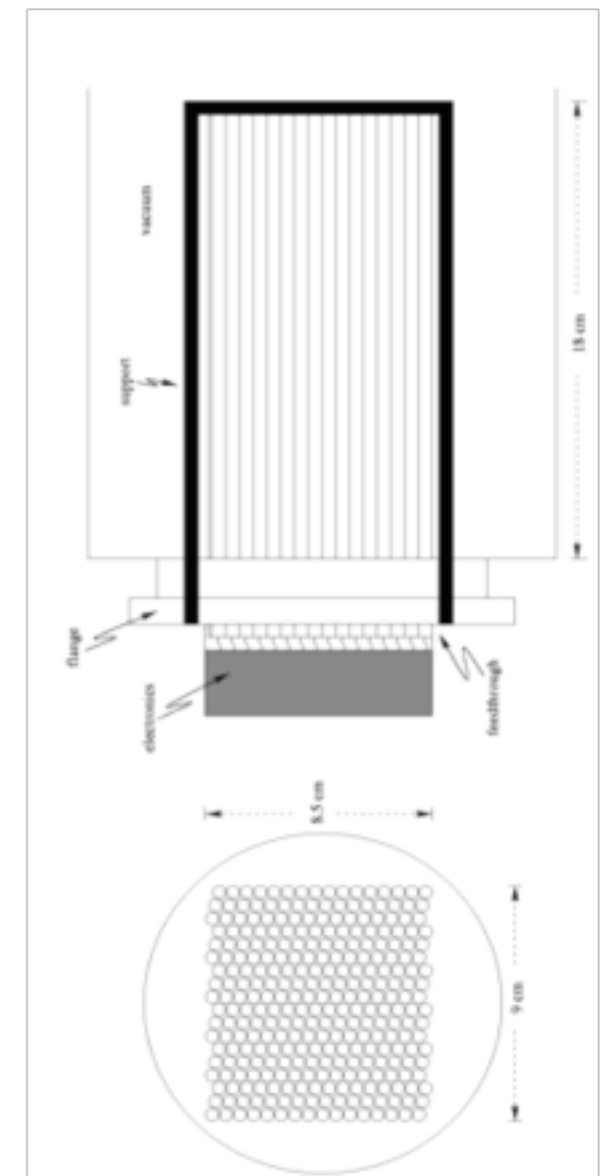
Tracking moved internal to the vacuum chamber



G-2 Muon EDM

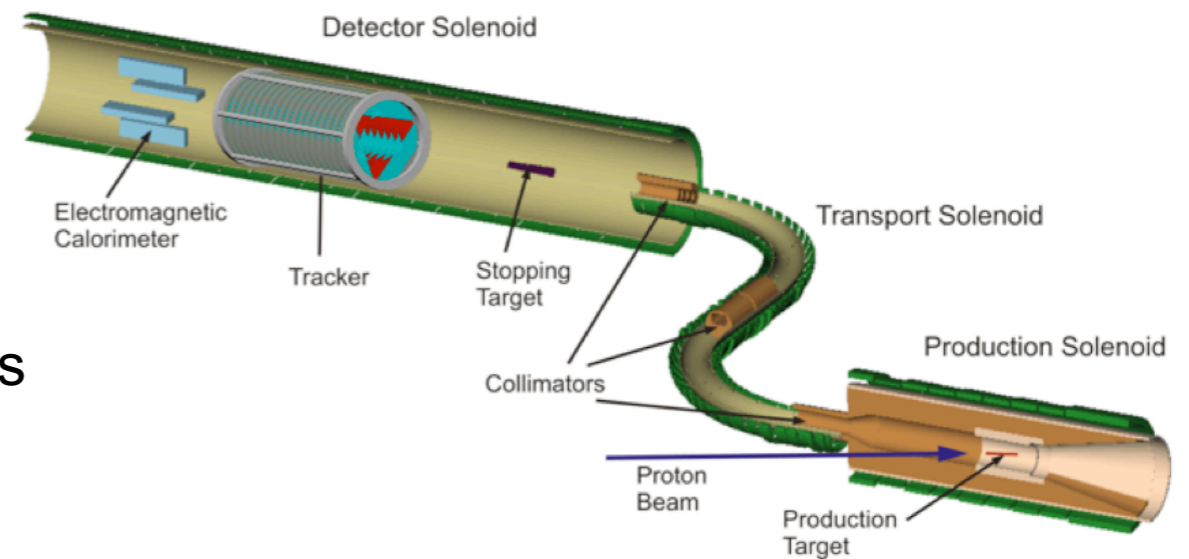


- EDM asymmetry is 90 degrees out of phase with g-2 asymmetry
 - When decay points into the ring versus out of the ring
 - Large flight length difference
 - Beam spread means higher acceptance for muons that point in
 - Need to define specs on knowledge of alignment and acceptance to get to the second order of magnitude

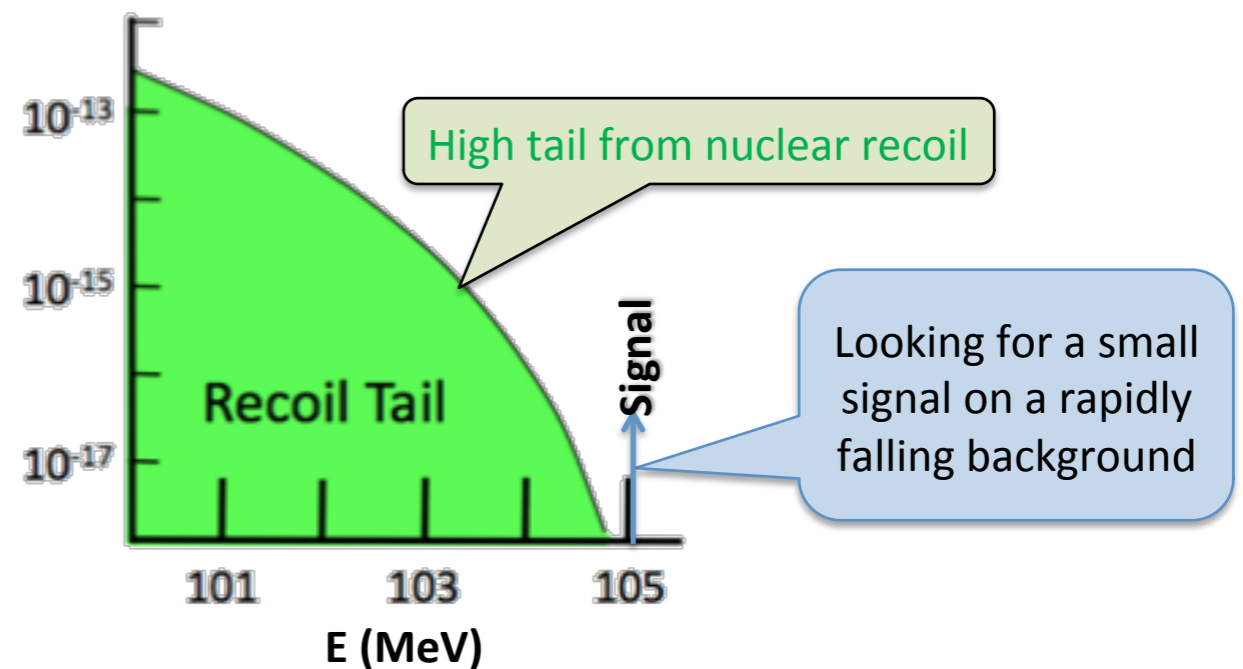
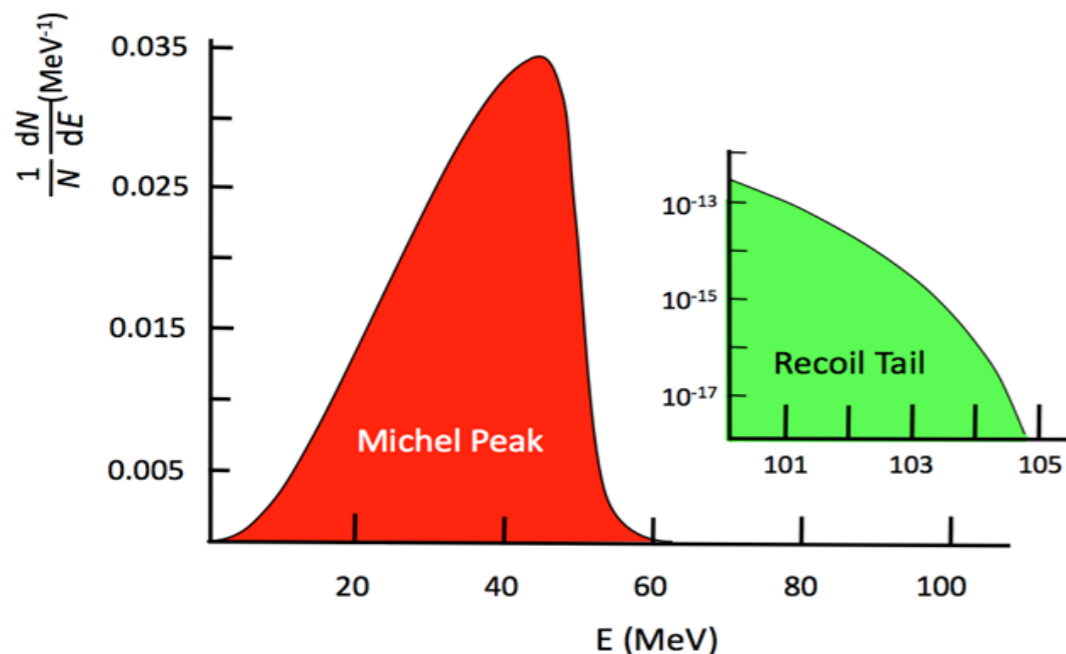


Mu to e Tracker (Mukherjee)

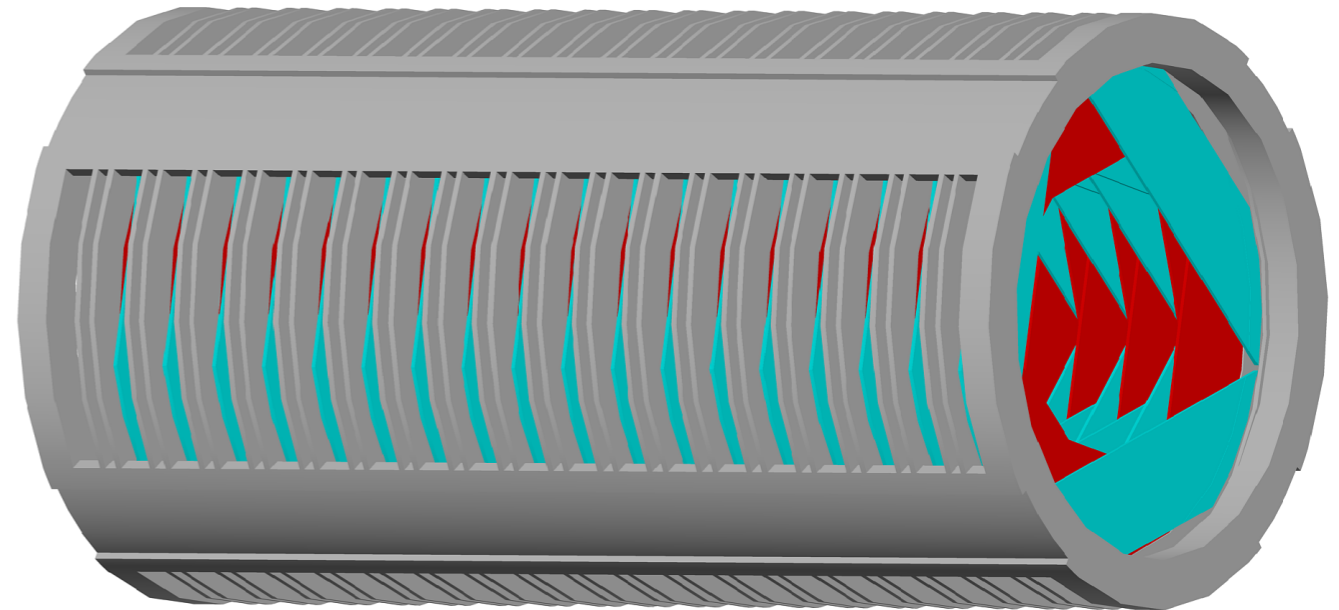
- Low energy muon beam strikes target
- μ ranges out in target, orbits nucleus
- Lifetime $\sim 700\text{nsec}$ in aluminum
 - $\sim 40\%$ muon capture $\mu^- + N \rightarrow \nu_\mu + N'$
 N' disintegration releases protons and neutrons
 - $\sim 60\%$ decay in orbit $\mu^- \rightarrow e^- + \nu_\mu + \nu_e$
 These “DIO” electron energy typically $< \frac{1}{2}$ the kinematic limit
- Hope a few do something more interesting



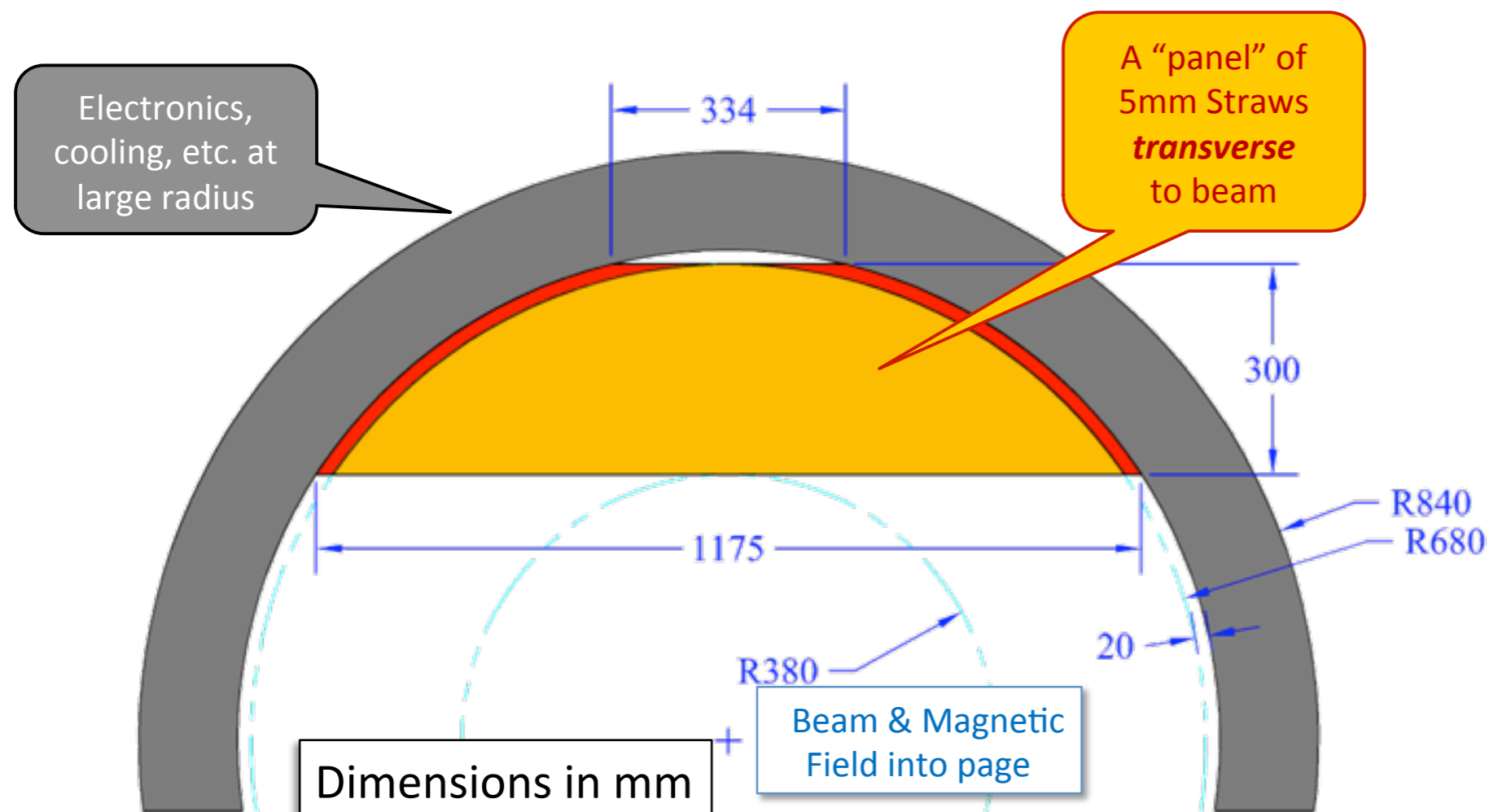
μ Decay in Orbit Spectrum for ^{27}Al



- 18 “stations” with straws transverse to beam
- Vacuum between stations to keep mass down
- Naturally moves readout and support to large radii



Basic Design



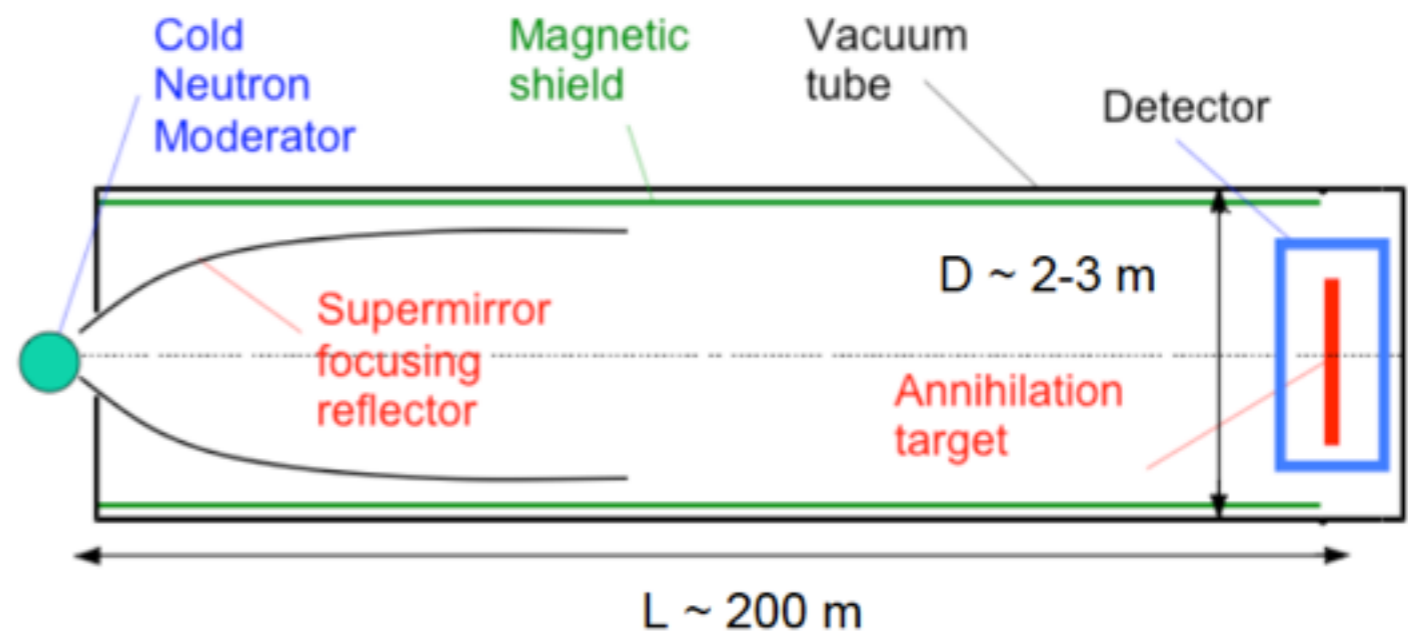
n n-bar oscillations (W. M. Snow)

For $\left[\frac{\sqrt{\alpha^2 + V^2}}{\hbar} t \right] \ll 1$ ("quasifree condition") $P_{n \rightarrow \bar{n}} = \left(\frac{\alpha}{\hbar} \times t \right)^2 = \left(\frac{t}{\tau_{n\bar{n}}} \right)^2$

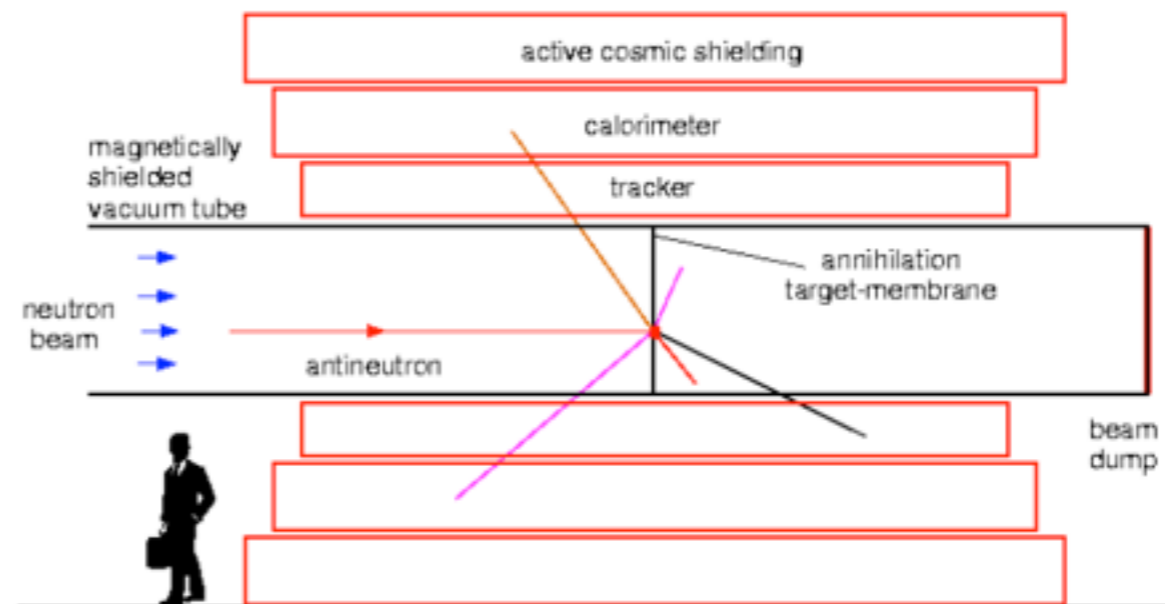
Figure of merit = NT^2 N=#neutrons, T="quasifree" observation time

Requirements:
excellent magnetic shielding
lots of cold neutrons

For tracker:
reconstruction of nbar annihilation event
- needs detailed study for optimization and quantification of requirements
- Straws probably a good candidate



The conceptual scheme of antineutron detector



Straw Chambers

Straws are the primary option for low mass (vacuum), high rate, moderate resolution. Chosen by G-2, $\mu \rightarrow e$, NA62.

- Limitations (Oh)

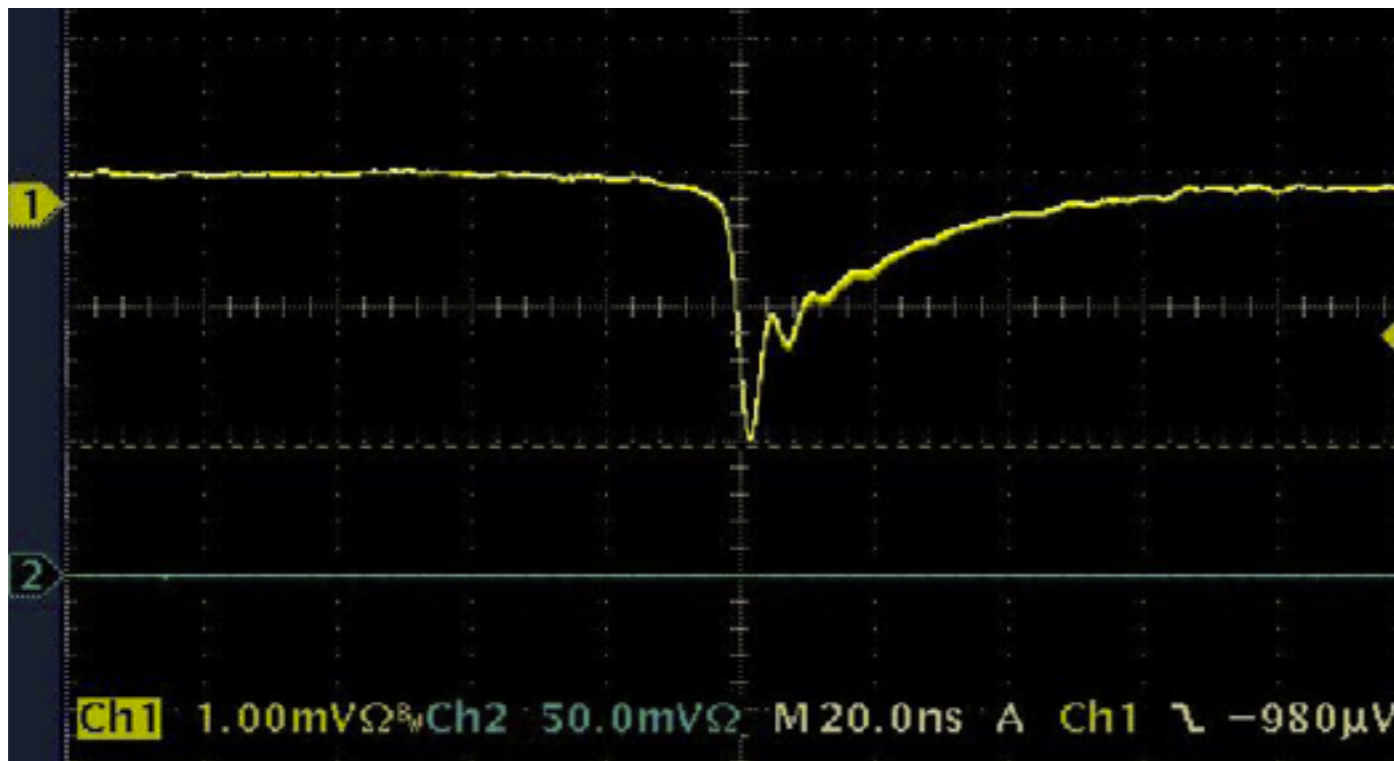
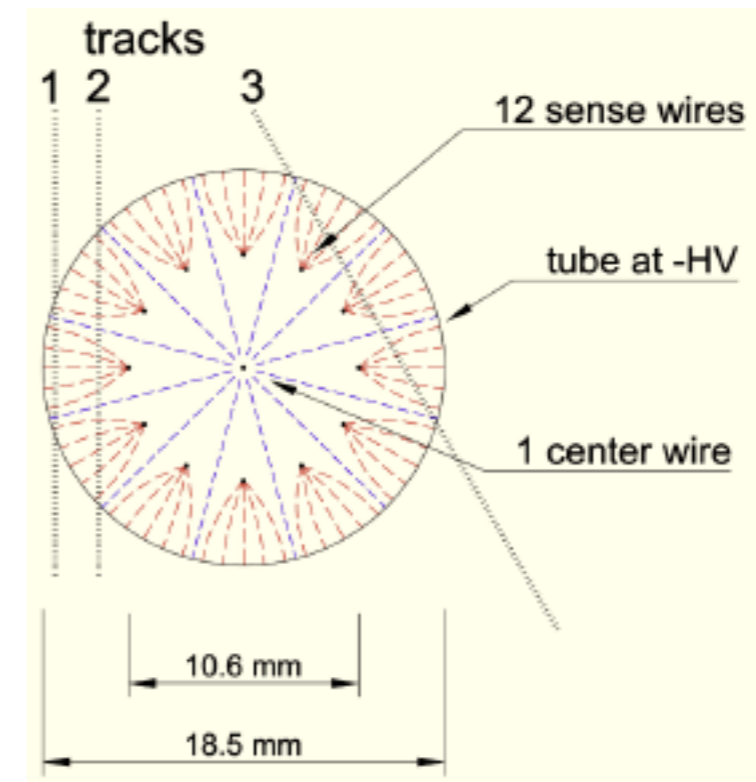
- Material
 - one tube/hit
- Difficulty of stringing for long straws (wire support)
- Difficulty of supporting stereo straws (or modules) in a cylindrical geometry
 - A detector with stereo has not yet been constructed



R&D - Multi-Anode Straws (Oh)

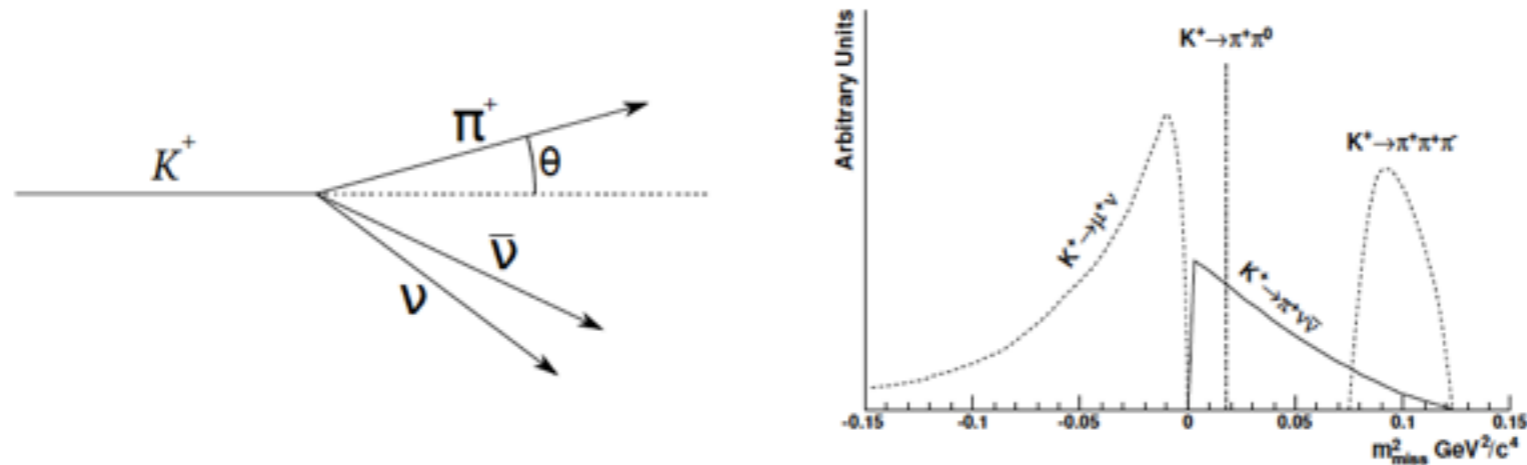
Straws used to be simple - why do this?

- Stereo - Rotate the wire plane at ends by some angle, (15 degrees in our prototype) in opposite direction.
- Multiple hits (<3>) per tube



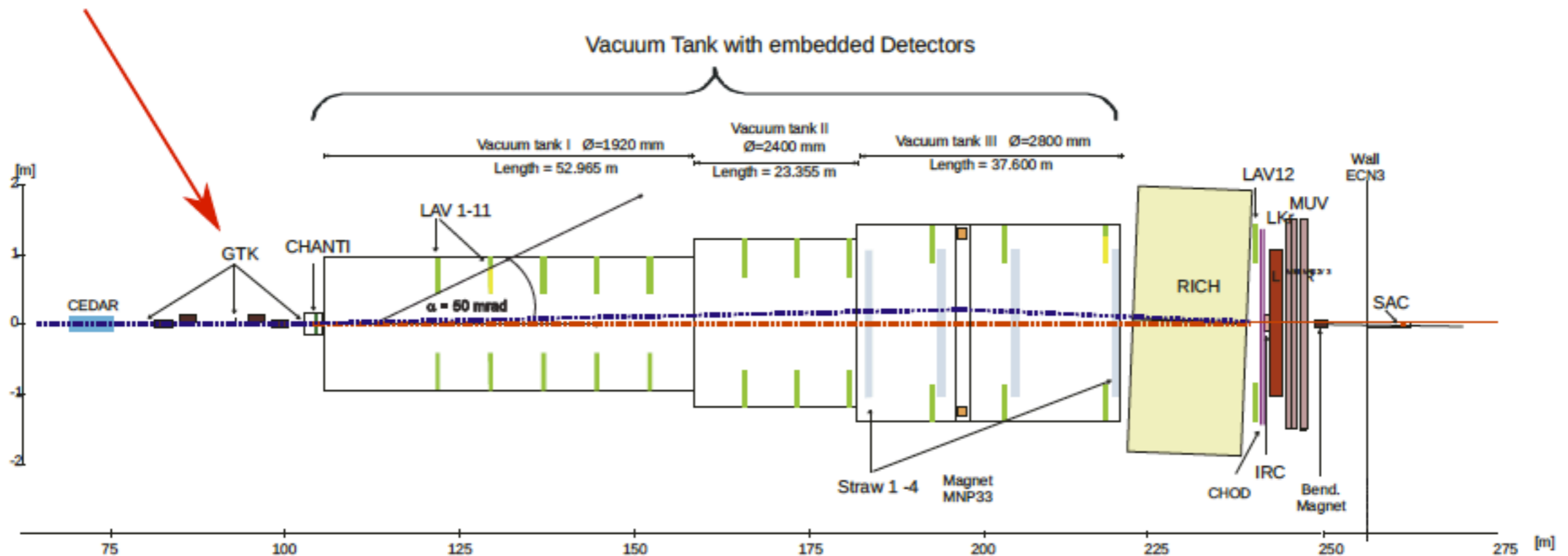
Silicon Tracking

NA62 Gigatracker (Velghe)



$$m_{\text{miss}}^2 = (p_k - p_\pi)^2 \approx m_K^2 \left(1 - \frac{|\mathbf{p}_\pi|}{|\mathbf{p}_K|}\right) + m_\pi^2 \left(1 - \frac{|\mathbf{p}_K|}{|\mathbf{p}_\pi|}\right) - |\mathbf{p}_\pi| |\mathbf{p}_K| \theta_{\pi K}^2$$

Impose requirements on GigaTracker:
 $\sigma(p_k)/p_k \approx 0.2\%$, $\sigma(\theta_k) \approx 16 \mu\text{rad}$, $\sigma(t) < 200 \text{ ps}$



GigaTracker (Velghe)

- Provides momentum, time of passage and direction of beam particles. Crucial for kinematic background rejection,
- Sees all beam particles, high and non-uniform rate, (1.3 MHz/mm² in the center, 750MHz total),
- Has to be as thin as possible to avoid inelastic scatterings.

Chip dimensions	12 × 19 mm ²
Chip thickness	100 μm [†]
Input dynamic range	0.6 – 10 fC
Electronic noise (with sensor)	200 e ⁻
Dissipated power (analog)	≈ 0.4 W/cm ²
Dissipated power (digital)	≈ 3.23 W/cm ²
Maximum rate per pixel	114 kHz
Maximum rate per chip	130 MHz

Each chip send data off via four 3.2 Gbit/s optical fibers (40 links per station)

- High digital and analog power
- Cooling is crucial

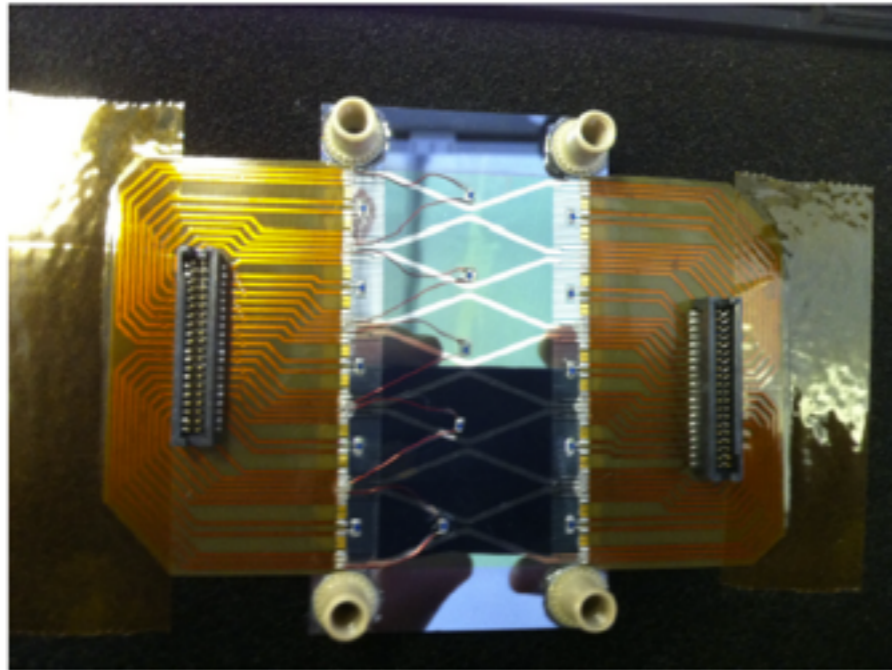
	# Pixels / chip	Pixel area [μm ²]	Idig [mA]	Iana [mA]	Power/ chip [mW]	Power/ pixel [μW]	Power density [mW/cm ²]
ALICE	8192	21'250	150	300	810	99	466
ATLAS	2880	20'000	35	75	190	67	335
CMS	4160	15'000	32	24	121	29	194

CMS no on-chip regulators 87 21 142

(R. Horisberger)

Gigatracker - Cooling and Performance (Velghe)

Baseline - micro channel cooling

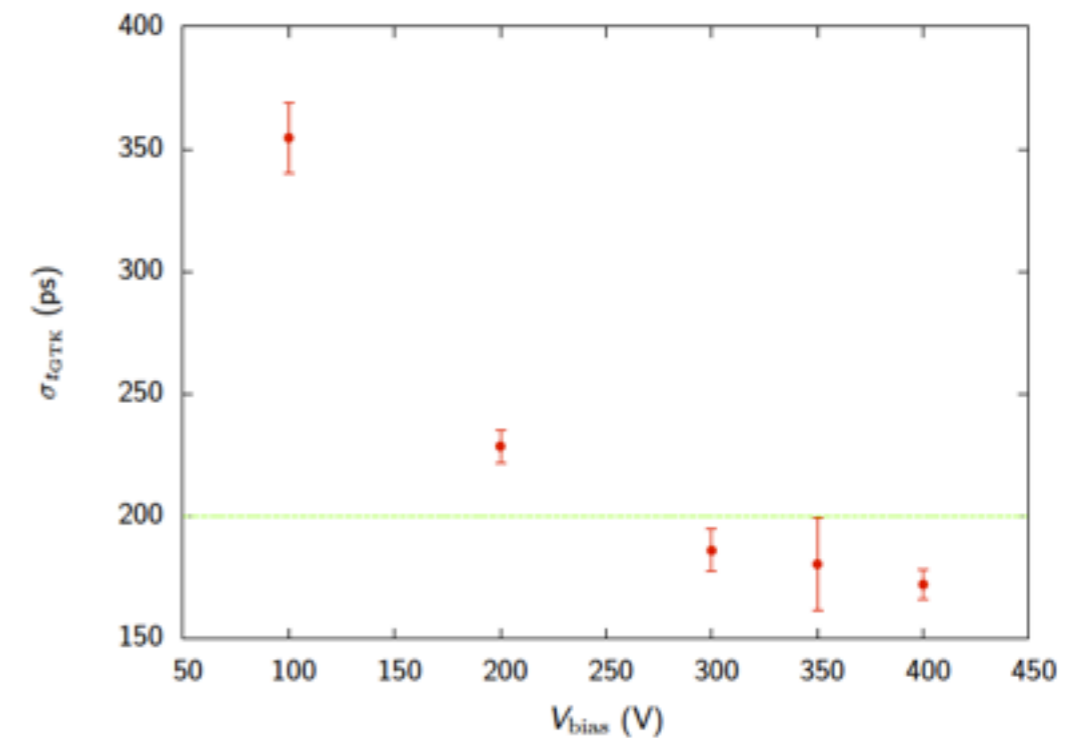
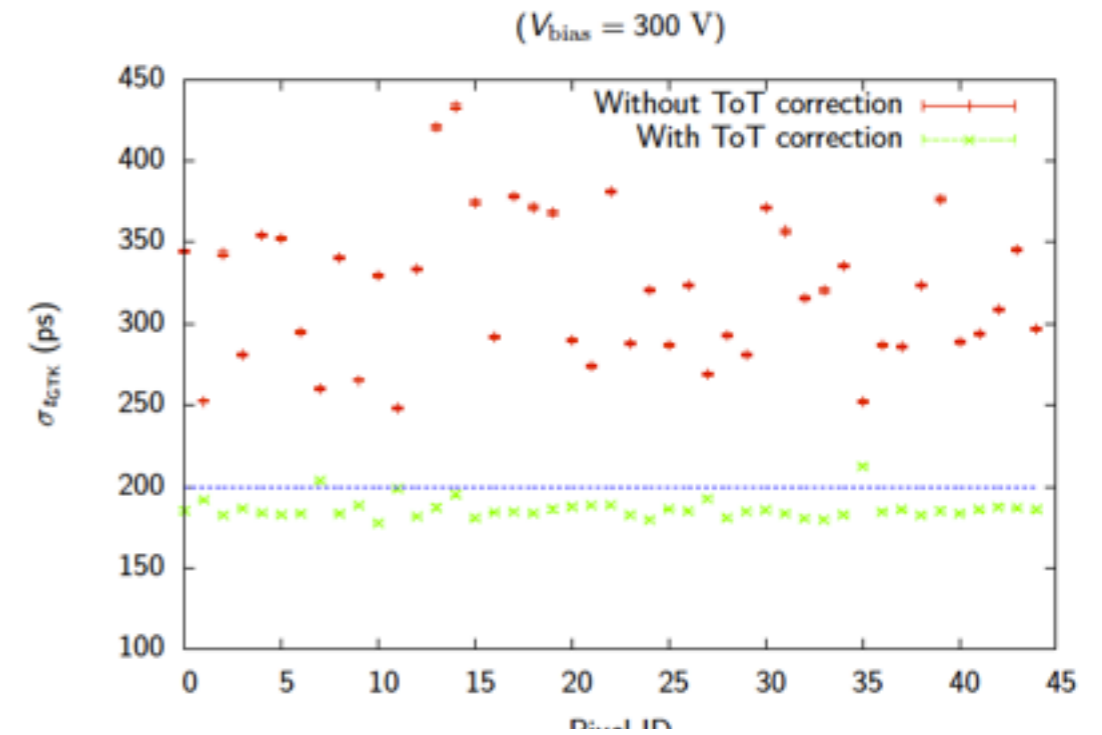


Material in the acceptance area: $0.13\%X_0$

Frame Option



45 pixel prototype performance

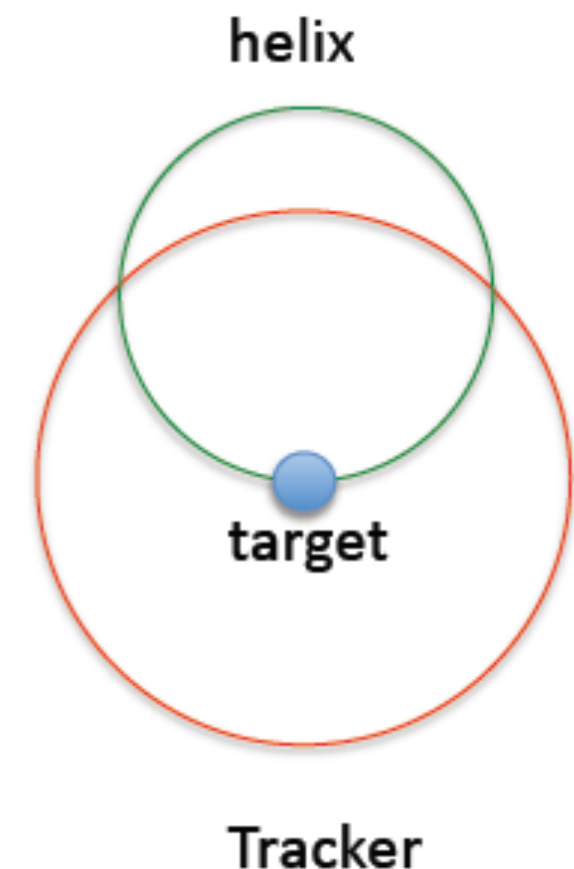


$\mu \rightarrow e\gamma$ with converted γ (DeJong)

- Goal: Path to 10^{-16} sensitivity using
 - Intense stopped muons beams from Project-X
 - Monolithic pixel detectors
 - Time of flight

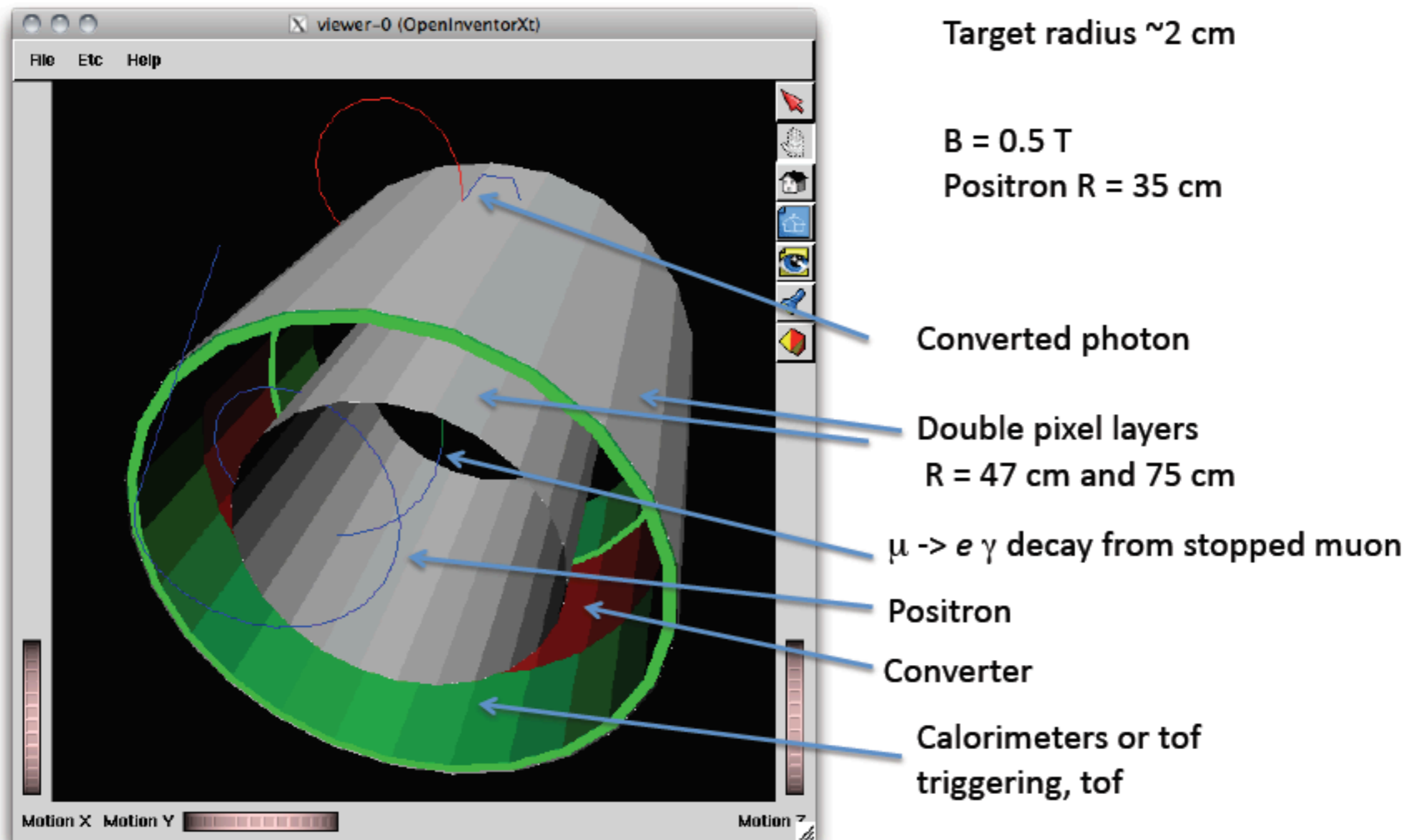
Moving forward with the converted photon approach:

- Use project X to increase R_μ (the rate of stopped muons) and signal rate
- **Problem: Accidental coincidence rate increases as R_μ^2 (instantaneous)**
- Need
 - 100% duty cycle
 - Thin converter
 - Thin detectors
 - Resolution limited only by energy loss and multiple scattering



$\mu \rightarrow e \gamma$ with converted γ (DeJong)

The simple minded geometry seems to work. Needs many m^2 pixel tracking



Many design constraints and options - need mass to convert photons, minimal mass for tracking, separation of layers, resolutions

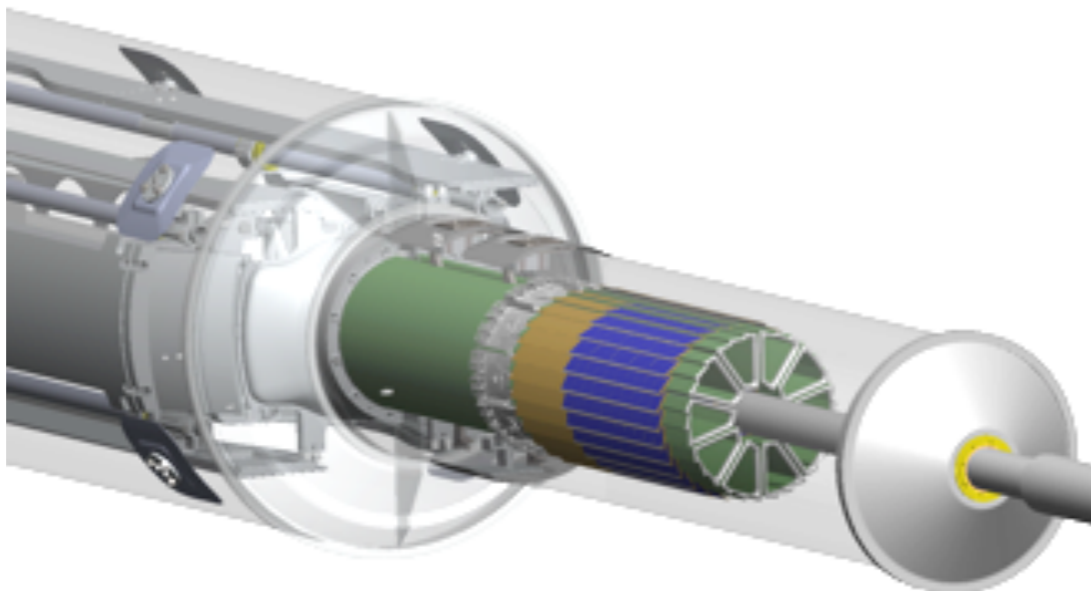
STAR Vertex (Greiner)

Requirements

- $-1 \leq \text{Eta} \leq 1$, full Phi coverage (TPC coverage)
- $\leq 30 \mu\text{m}$ DCA pointing resolution required for 750 MeV/c kaon
 - Two or more layers with a separation of $> 5 \text{ cm}$.
 - Pixel size of $\leq 30 \mu\text{m}$
 - Radiation length as low as possible but should be $\leq 0.5\%$ / layer (including support structure). The goal is 0.37% / layer
- Integration time of $< 200 \mu\text{s}$
- Sensor efficiency $\geq 99\%$ with accidental rate $\leq 10^{-4}$.
- Survive radiation environment.
- Upgrade detector – fit into existing STAR infrastructure (trigger, DAQ, etc.)

Design Choices

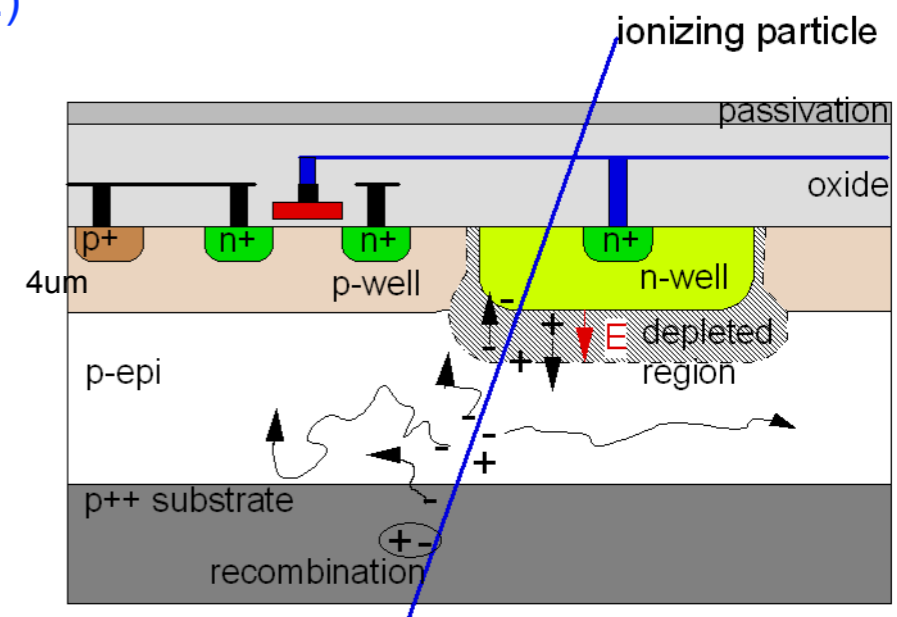
- Air cooling
- Thinned silicon sensors ($50 \mu\text{m}$ thickness)
- MAPS (Monolithic Active Pixel Sensor) pixel technology
 - Sensor power dissipation $\sim 170 \text{ mW/cm}^2$
 - Sensor integration time $< 200 \mu\text{s}$ ($L=8 \times 10^{27}$)
- Quick extraction and detector replacement (1 day)



CMOS Pixel technology

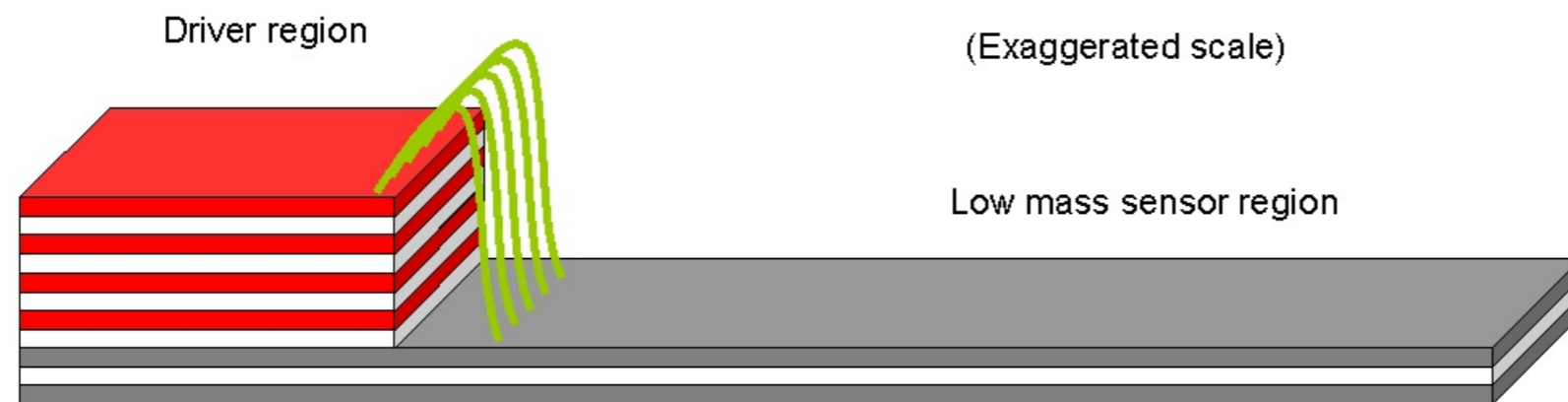
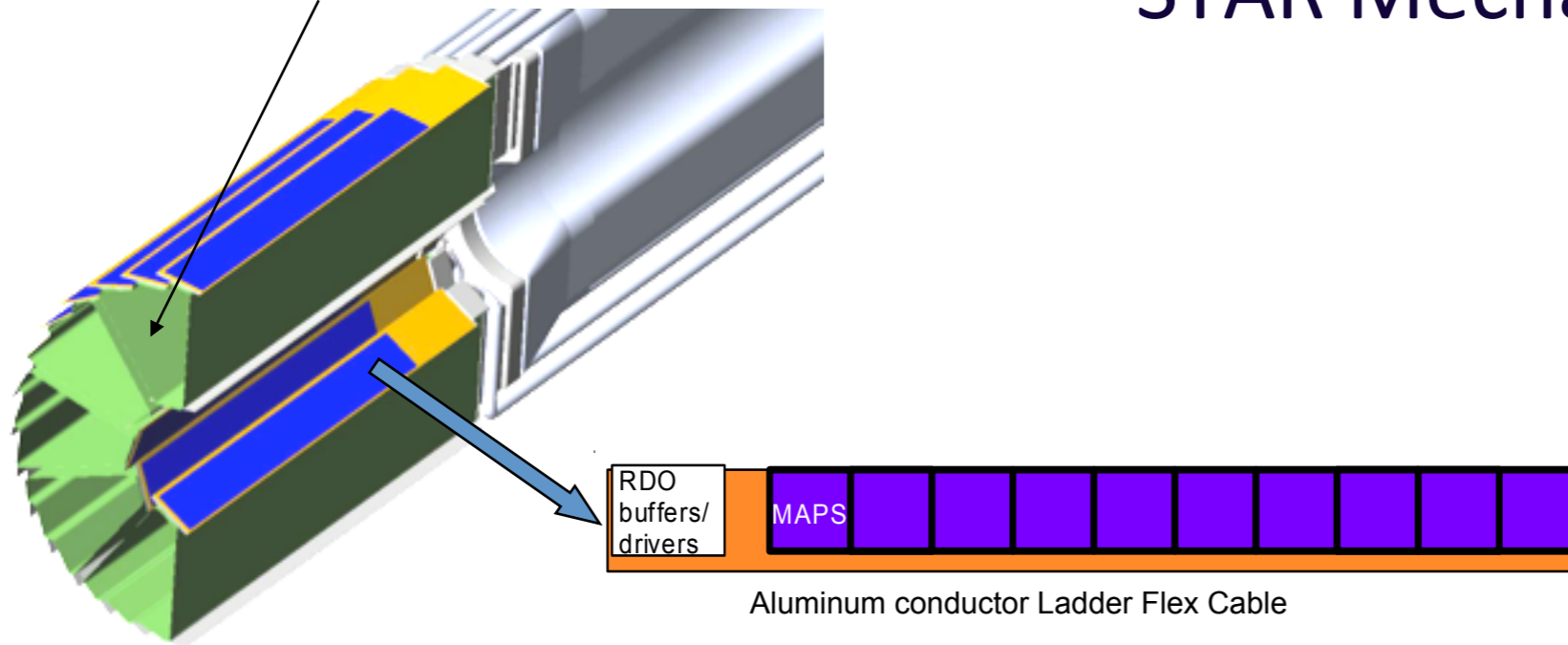
- Standard process
- Low mass
- long charge collection
- Excellent position resolution

MAPS pixel cross-section (not to scale)

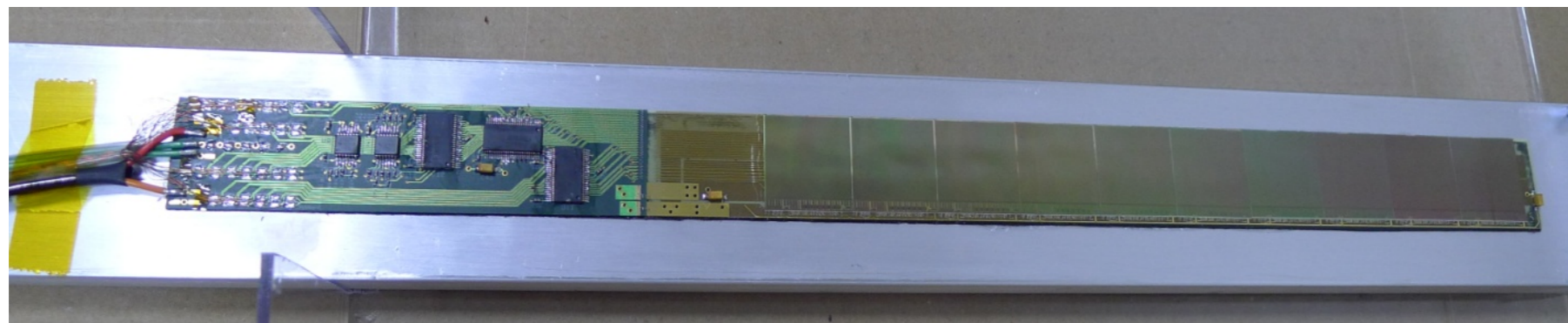


STAR Mechanics (Greiner)

carbon fiber sector tubes
(~ 200 μm thick)



Low mass region calculated X/X_0 for Al conductor = 0.073 %
Low mass region calculated X/X_0 for Cu conductor = 0.232 %



Low Mass Mechanics (Cooper)

Support structures normally rely upon unidirectional carbon fiber because of its favorable elastic modulus to mass and radiation length ratios.

A common fiber for low-mass structures is Mitsubishi K13C2U.

Fiber elastic modulus = 130 MSI (4.45 that of stainless steel).

Normally obtained as “prepreg” with either epoxy or cyanate ester resin.

K13D2U has a slightly higher modulus, but is more difficult to handle.

Unidirectional prepreg is normally “laid up” in several layers (6-8) to form laminate.

The angle of each layer is chosen to control laminate properties.

Cure at 250 - 275 °F and 1 - 5 atmospheres pressure.

Cured laminate is roughly 50% fiber and 50% resin by volume.

Laminate elastic modulus 24 MSI for a quasi-isotropic lay-up (~80% that of stainless steel).

Typically, cured fiber ply thickness is 57-63 μm .

Depends on the amount of resin removed during cure.

X/X0 per ply 0.025%.

SiD/D0 CF Support Cylinders

Carbon fiber - Rohacell - carbon fiber support cylinders were developed for the D0 fiber tracker.

Similar cylinders were used by ATLAS for silicon support.

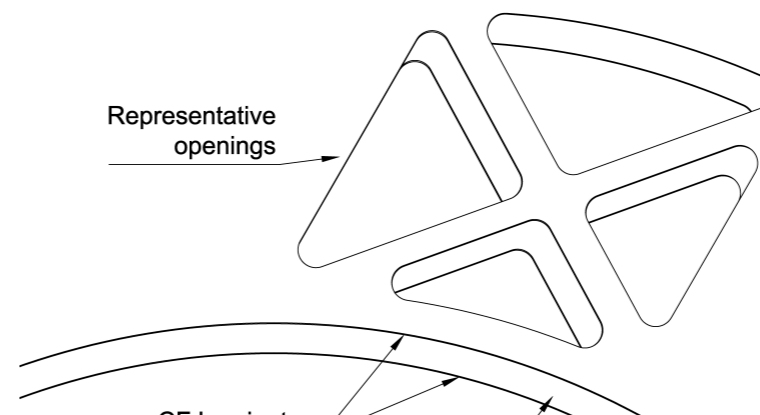
The two carbon fiber (CF) laminate layers (3 plies of Mitsubishi K1392U fiber per layer), in conjunction with a 8.9 mm Rohacell spacer, provide out-of-round stiffness (0.23% X0 total per cylinder).

Longitudinal stiffness is provided by the carbon fiber itself.

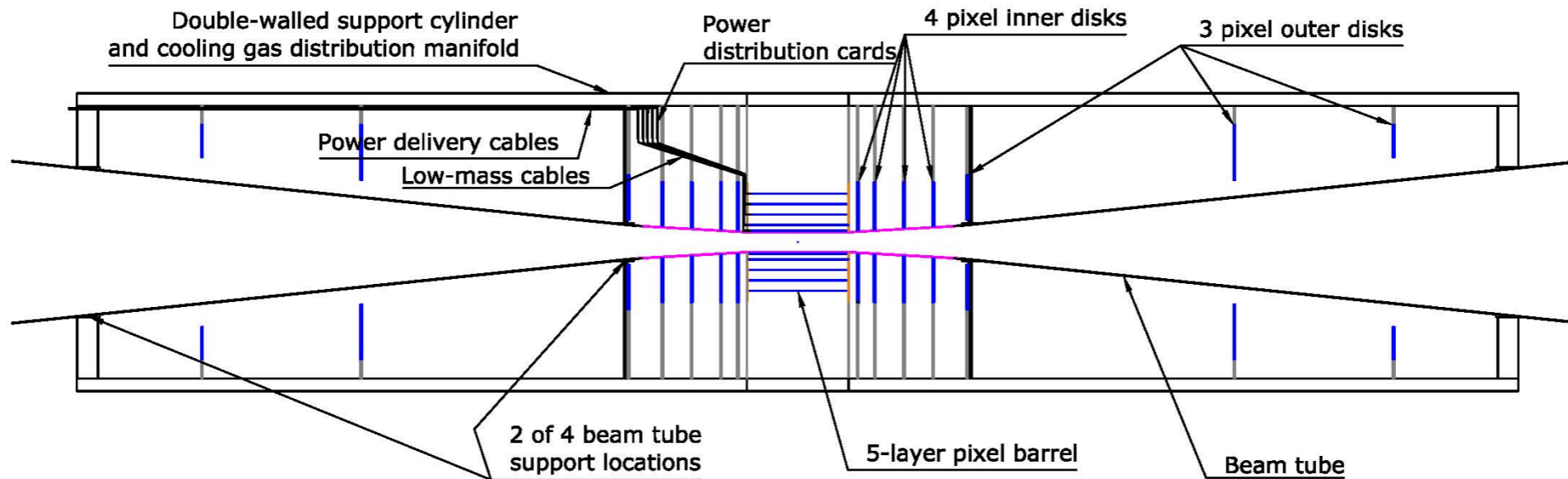
Carbon fiber laminate end rings with ball and cone mounts tie barrels to one another, help with out-of-round stiffness, and provide a location and support for power conditioning and distribution.

Finite element analysis (FEA) gave a maximum (local) deflection from gravity of $\sim 13 \mu\text{m}$.

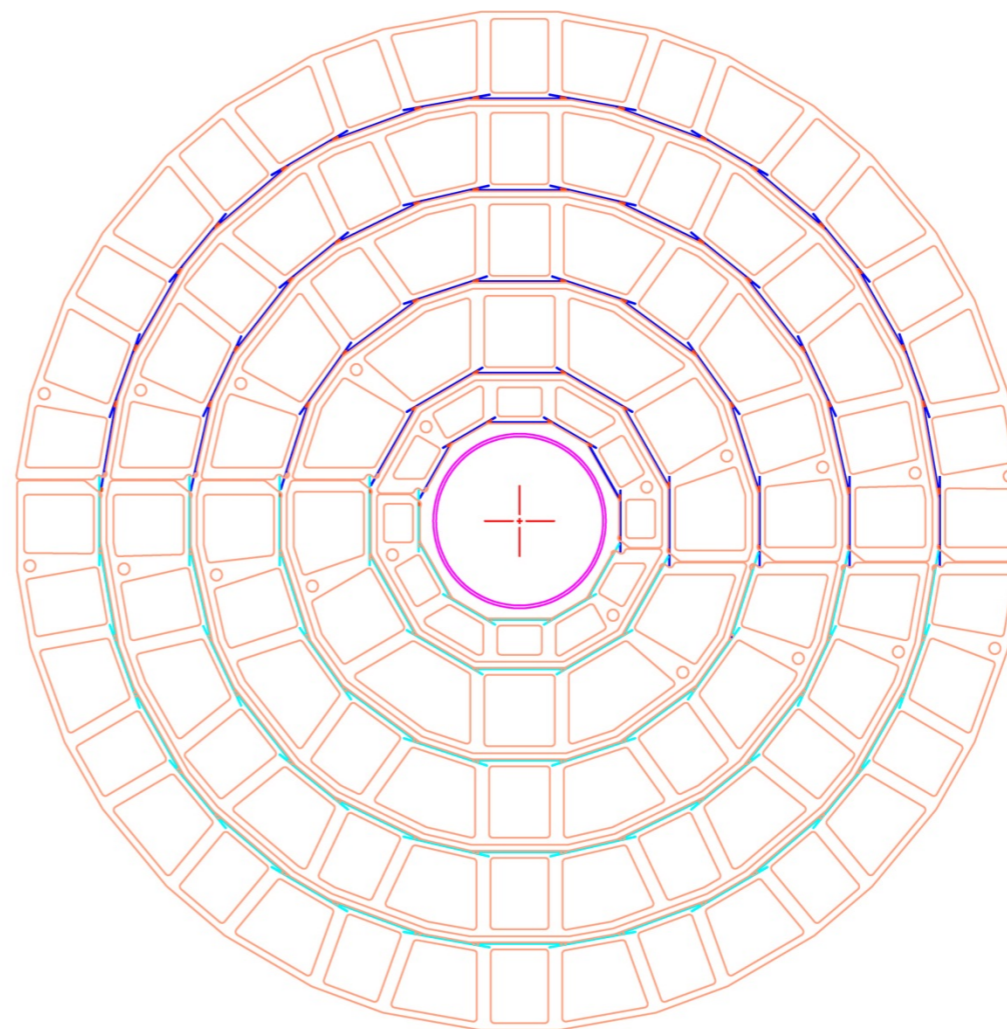
Openings can be cut to reduce average material but were not assumed in the FEA.



ILC Vertex (SiD) (Cooper)

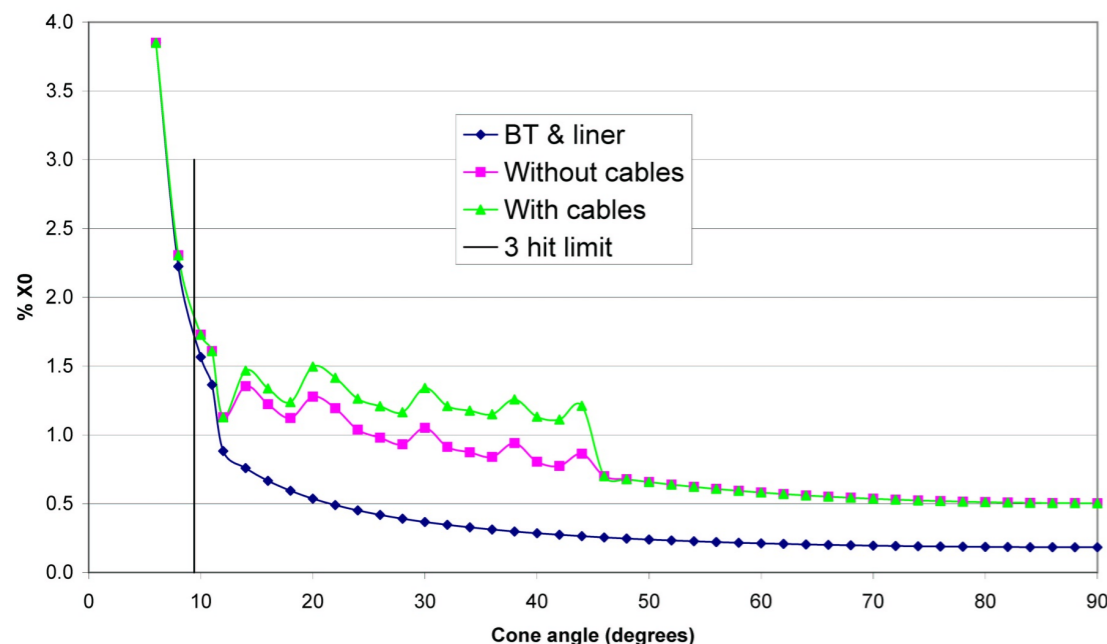


- Goal = 0.1% X_0 per layer (+ cables)
- Sensors glued to one another along edges and supported from ends
- 75 μm silicon thickness assumed (3D sensors)
- Could be modified for thicker or thinner sensors



Sensor active widths:
 L1: 8.6 mm
 L2 - L5: 12.5 mm
 Cut - active width: 0.08 mm
 Inner radii:
 A-layer: 14, 21, 34, 47, 60 mm
 B-layer: 14.4593, 21.4965, 34.4510, 47.3944, 60.3546 mm
 Sensors per layer:
 12, 12, 20, 28, 36
 Sensor-sensor gap: 0.1 mm
 Sensor thickness: 0.075 mm
 7 June 2007, 14 August 2007

Material in front of last VTX Layer Hit, Barrels + Disks

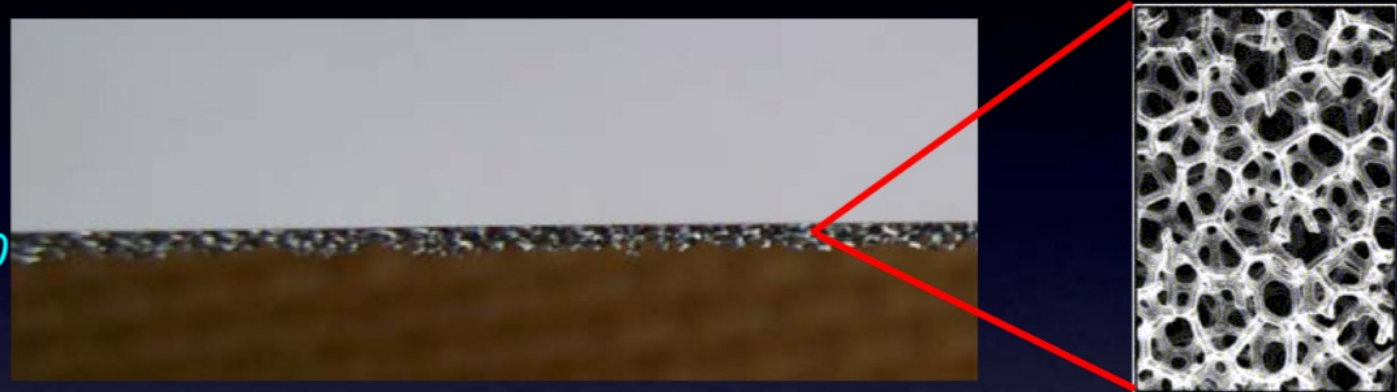




Foam Ladders

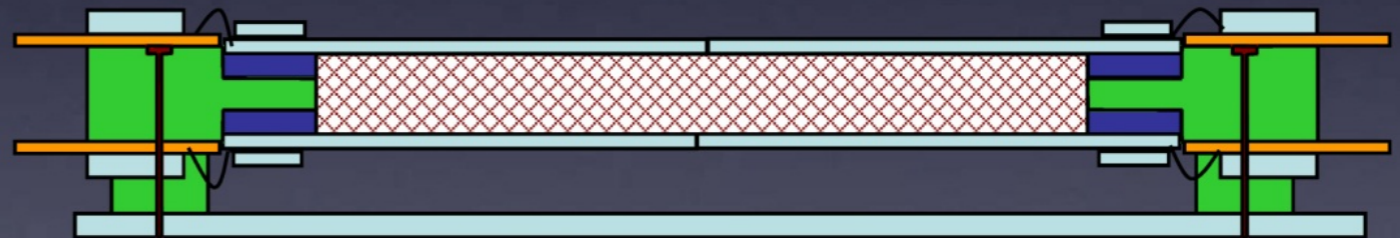
- 25 micron silicon on 1.5mm 8% SiC

- ▶ Very rigid
- ▶ Achieved 0.14% X_0



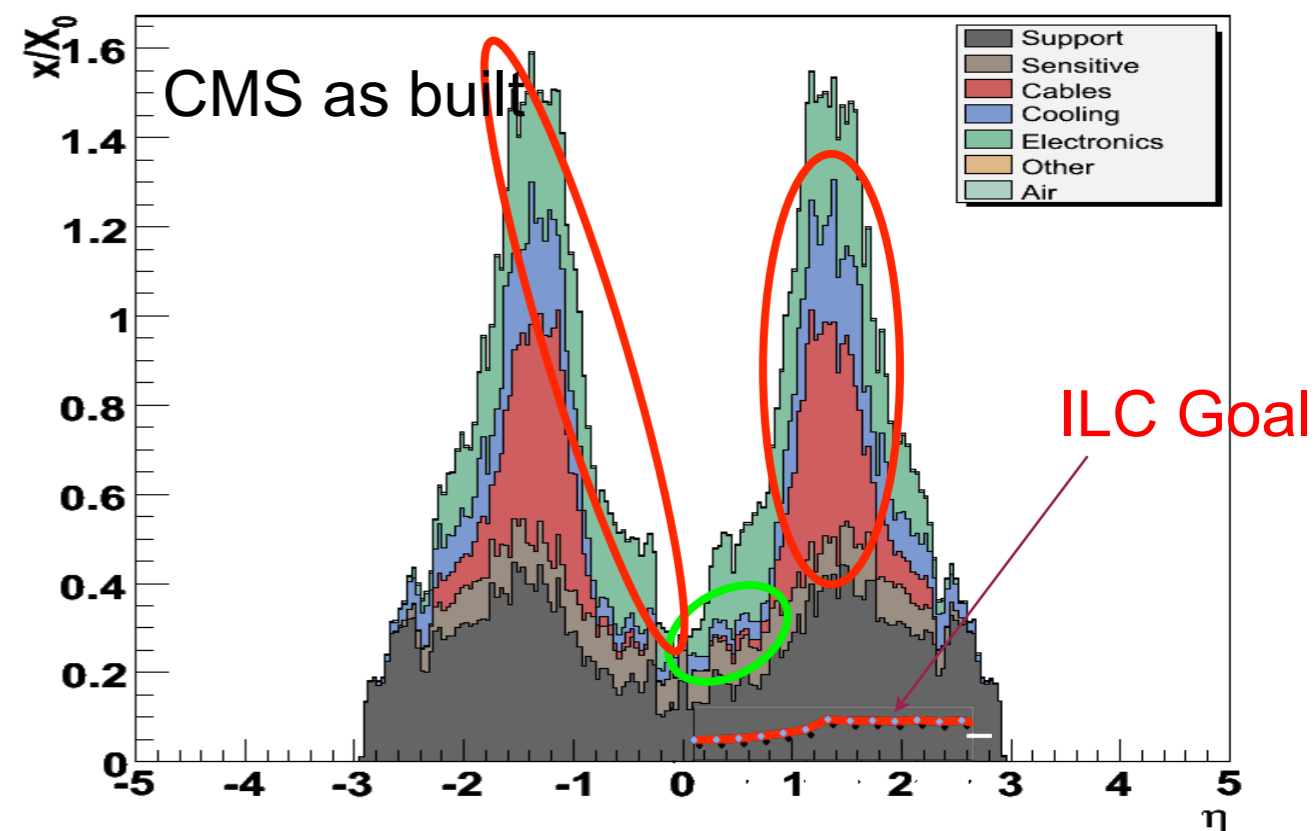
- 20 micron silicon sandwiching 1.5mm 2% carbon

- ▶ Could be double-sided
- ▶ Achieved 0.07% X_0



Power Consumption

- Limiting Power consumption is crucial for low mass pixelated detectors (CMS Tracker- 17 kAmp)
- Move electronics off-detector
- Limit power to allow air cooling
- Use CO₂ cooling
- There are basic power-speed and detector tradeoffs



	# Pixels / chip	Pixel area [μm^2]	Idig [mA]	Iana [mA]	Power/ chip [mW]	Power/ pixel [μW]	Power density [mW/cm^2]
ALICE	8192	21'250	150	300	810	99	466
ATLAS	2880	20'000	35	75	190	67	335
CMS	4160	15'000	32	24	121	29	194

CMS no on-chip regulators 87 21 142

(R. Horisberger)

How to build a fast, low power silicon tracker

1. Minimize Collection time

Collect electrons ($\mu_e=1350$ cm/V*sec, $\mu_h=450$ cm/V*sec)

2. Fast amplifier

$T_r \sim 0.35/f_u$, $f_u \sim g_m/(2\pi C_{gs})$, **High transistor transductance g_m**

3. Good signal/noise

$\sigma_t \sim T_r/(S/N) \sim 1/(g_m * S/N)$

4. Low noise, high signal

- $(S/N)^2 \sim Q_s^2(1/(4kT\Delta f) (g_m/C_d^2))$, thick detector, short strips
- $\text{Noise}^2 \sim 1/g_m \sim 1/I_d$ – direct power penalty

Minimize detector thickness for short collection time

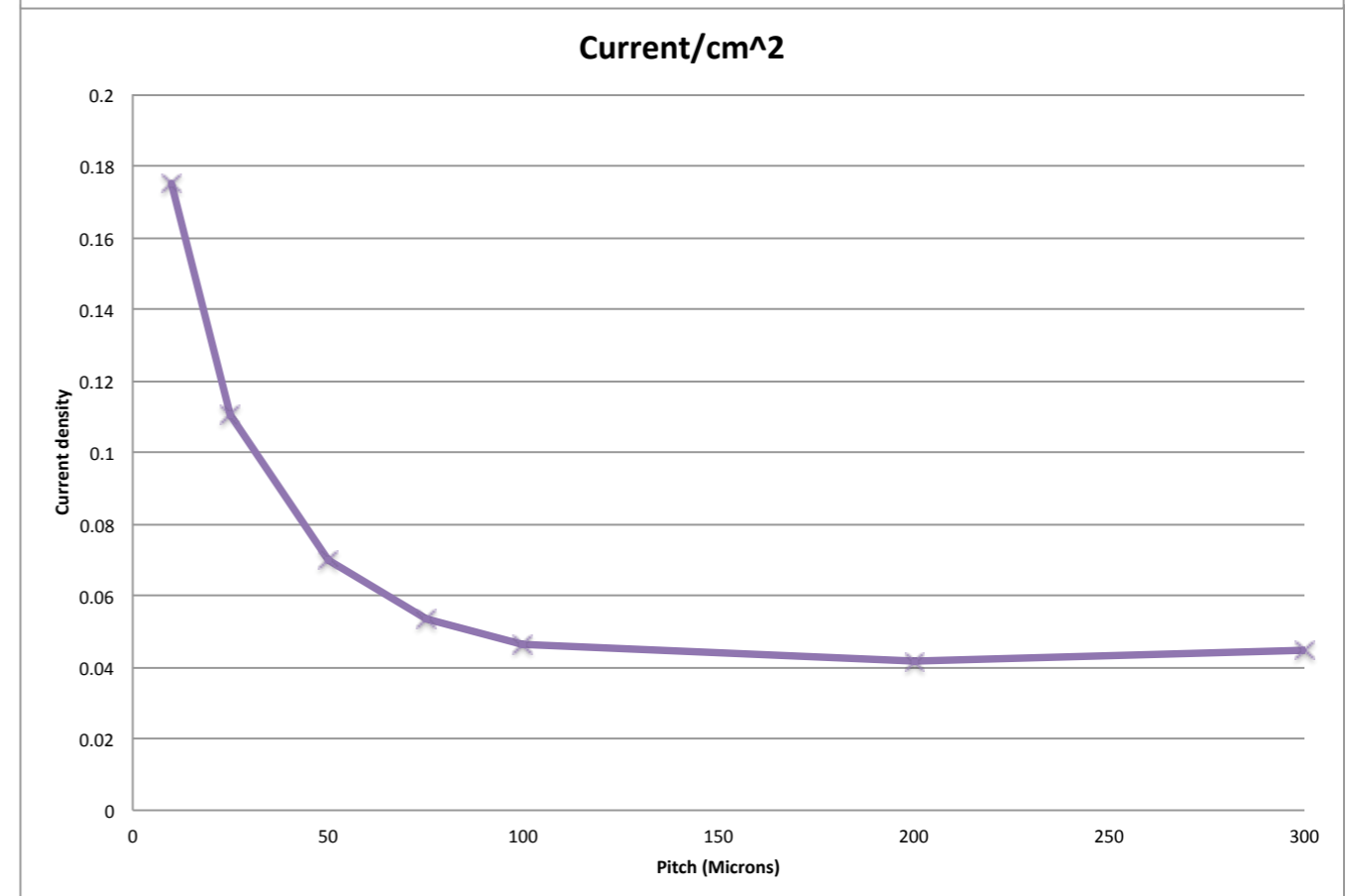
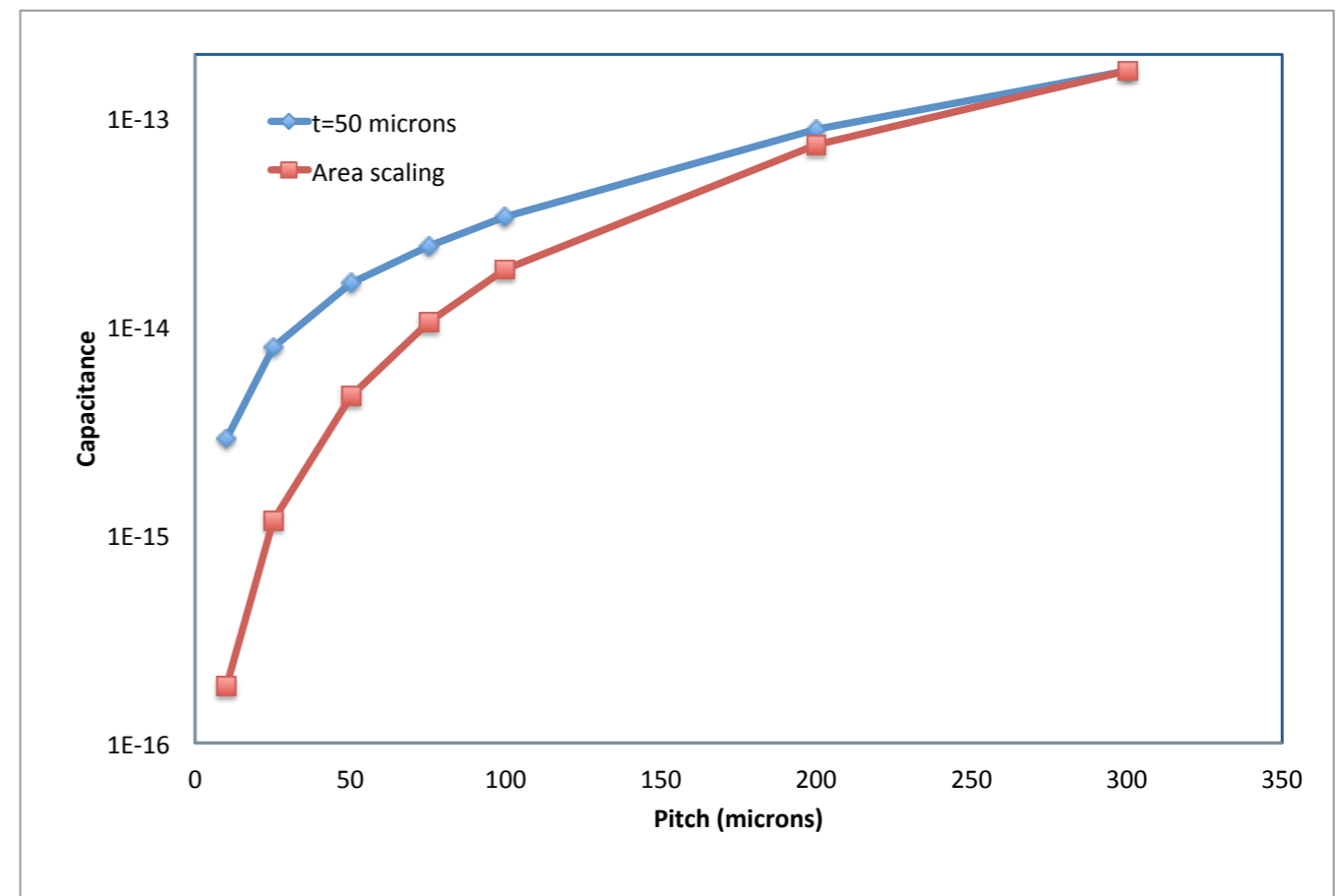
Maximize detector thickness for low C_d , high Q

Pixel Pitch Scaling

Do we pay for smaller pixels?
(Real workshop calculation -
probably wrong)

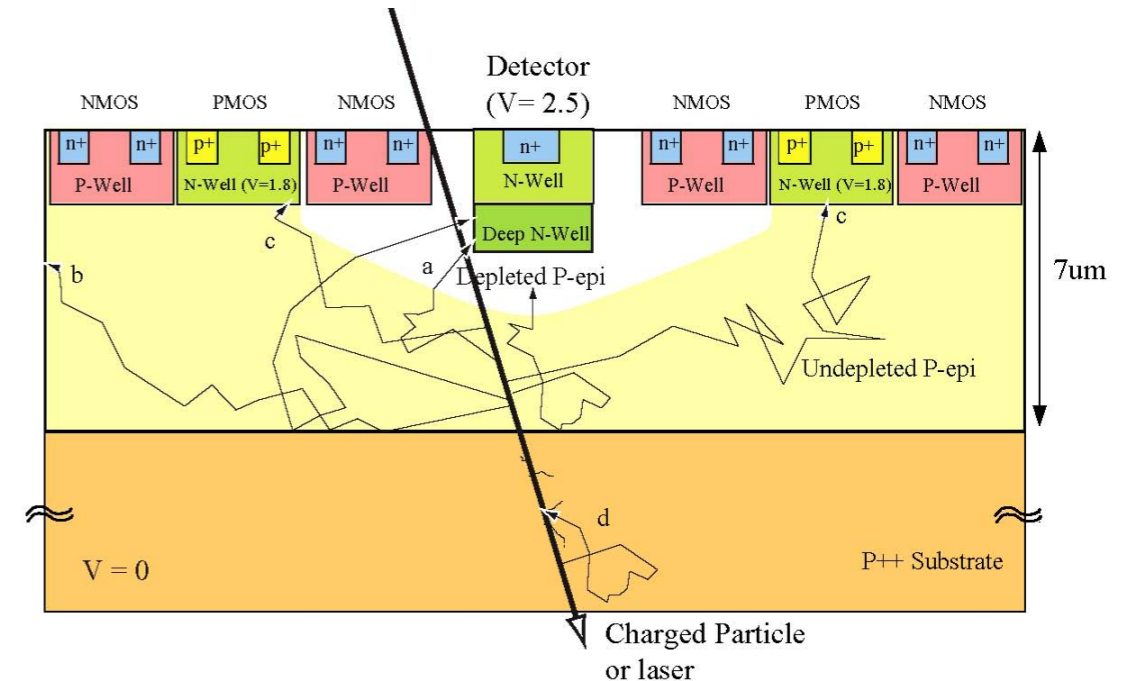
CMOS amp in weak inversion

- Rise time $t_r \sim \text{ratio } C_d/g_m$
- Signal/noise $\sim \text{ratio } \text{Sqrt}(g_m)/C_d$
- Constant time resolution-
maintain ratio:
 $t_r/(S/N) \sim C_d^2/g_m^{3/2}$

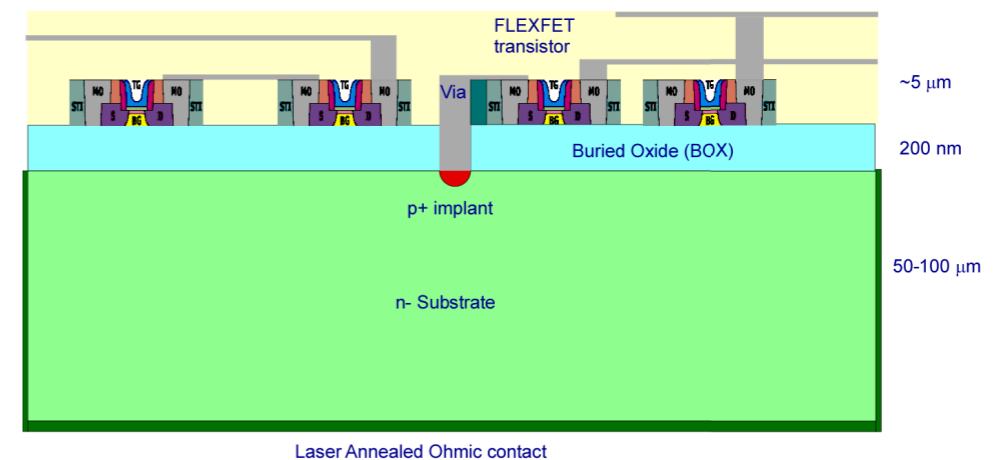


Low Mass Silicon R&D

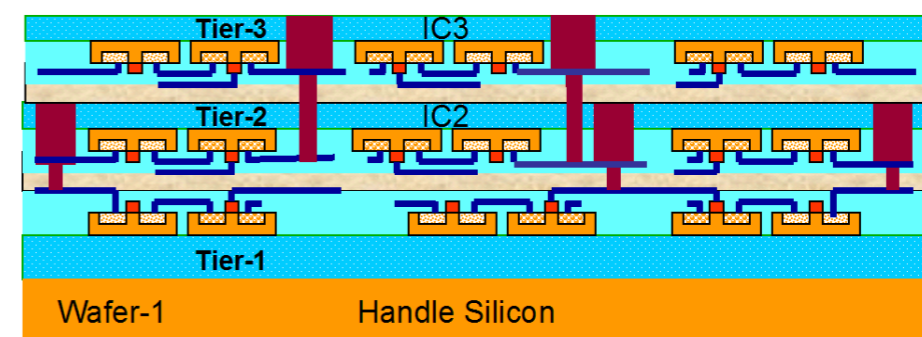
- We know we can get good S/N with thin, pixelated detectors - what technologies are available to achieve this?
- Much R&D related to ILC which requires $<.1\%$ RI per layer
- Too much to go over details in a brief talk - but there are many choices. I will concentrate on FNAL work



CMOS Active Pixels



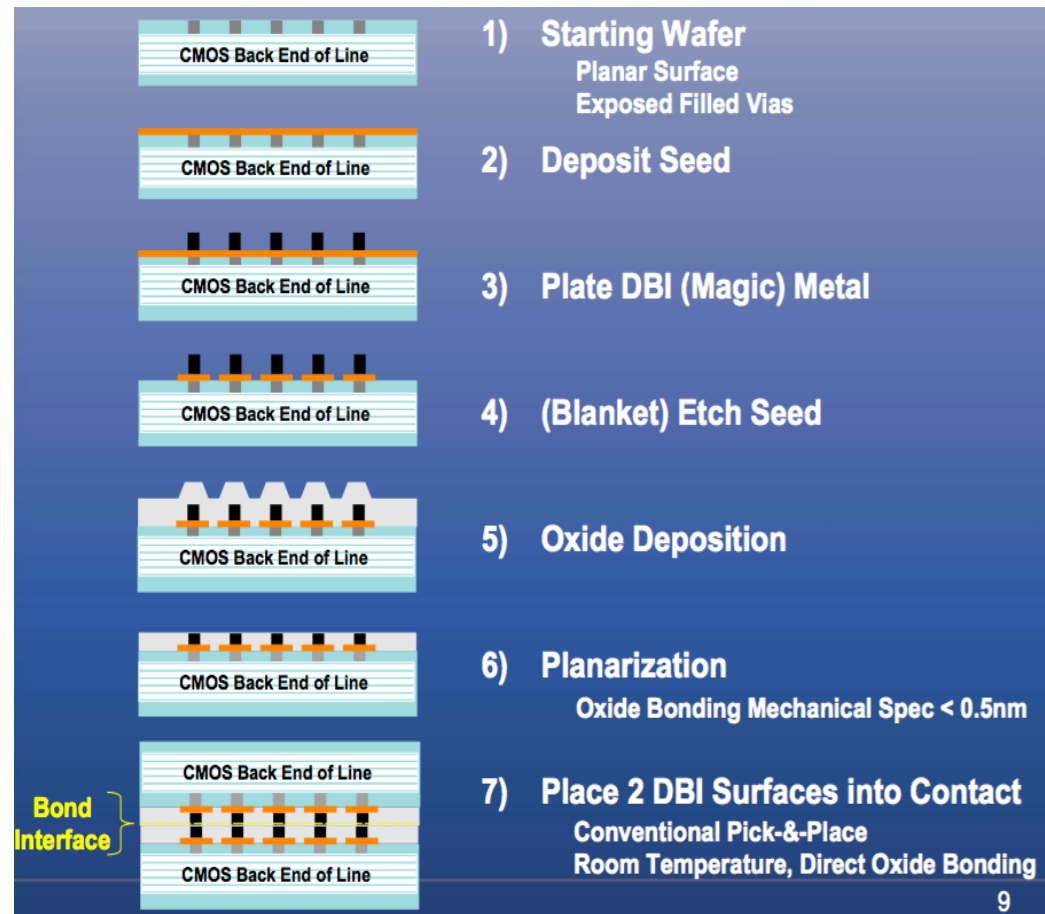
SOI



3D

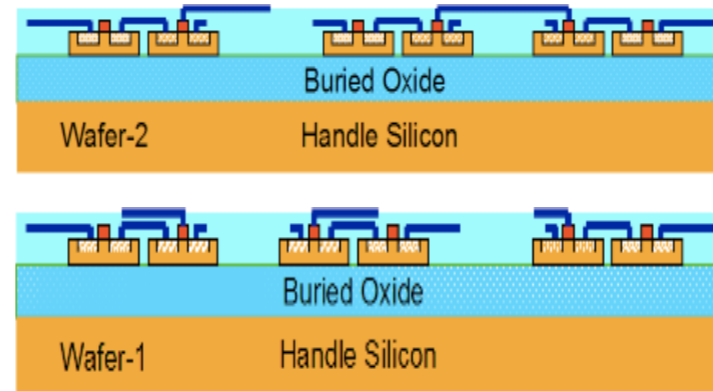
Processes Explored

Ziptronix Oxide Bonding

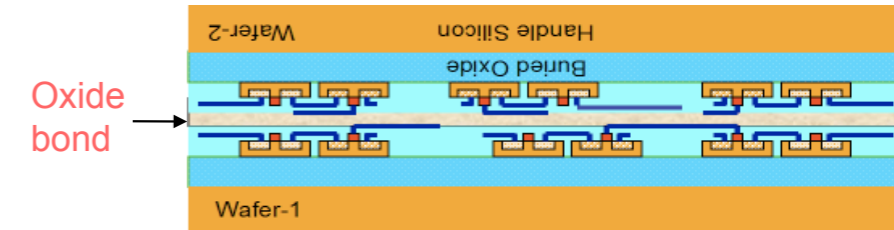


MIT-LL Oxide wafer bonding

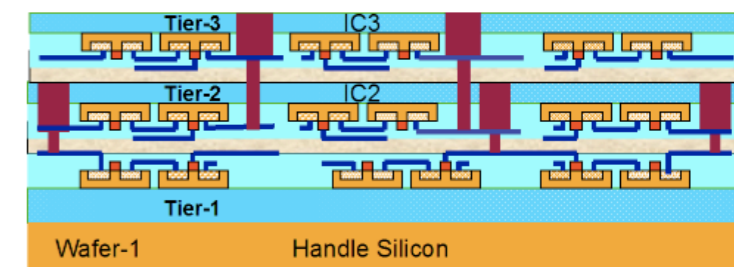
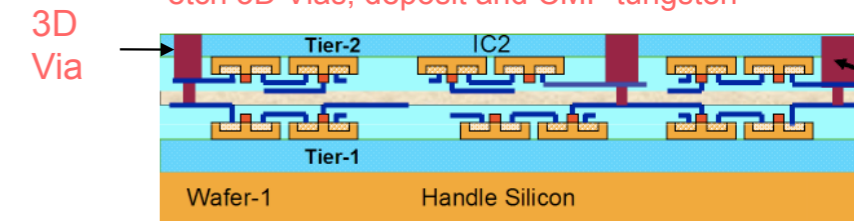
1) Fabricate individual tiers



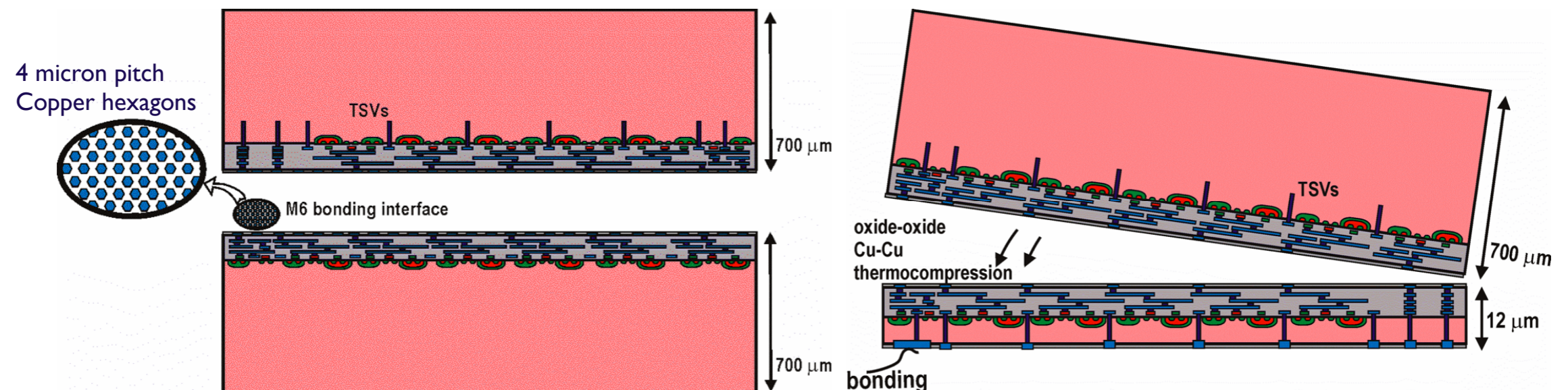
2) Invert, align, and bond wafer 2 to wafer 1



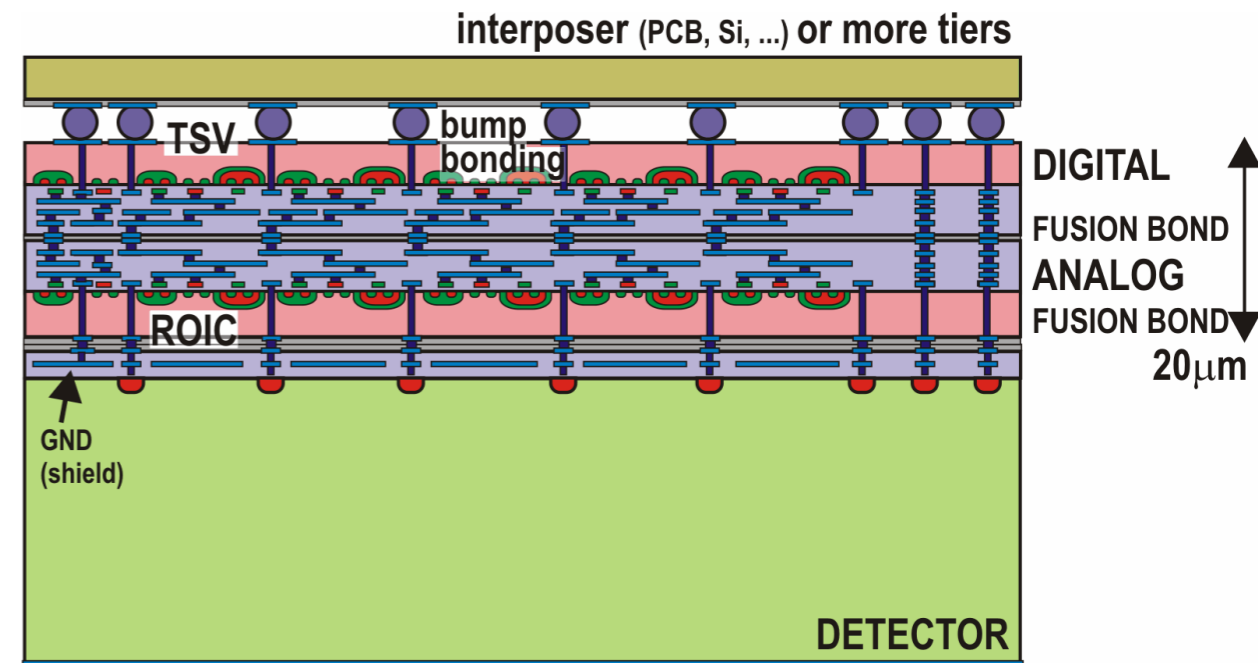
3) Remove handle silicon from wafer 2, etch 3D Vias, deposit and CMP tungsten



Tezzaron cu-cu bonding



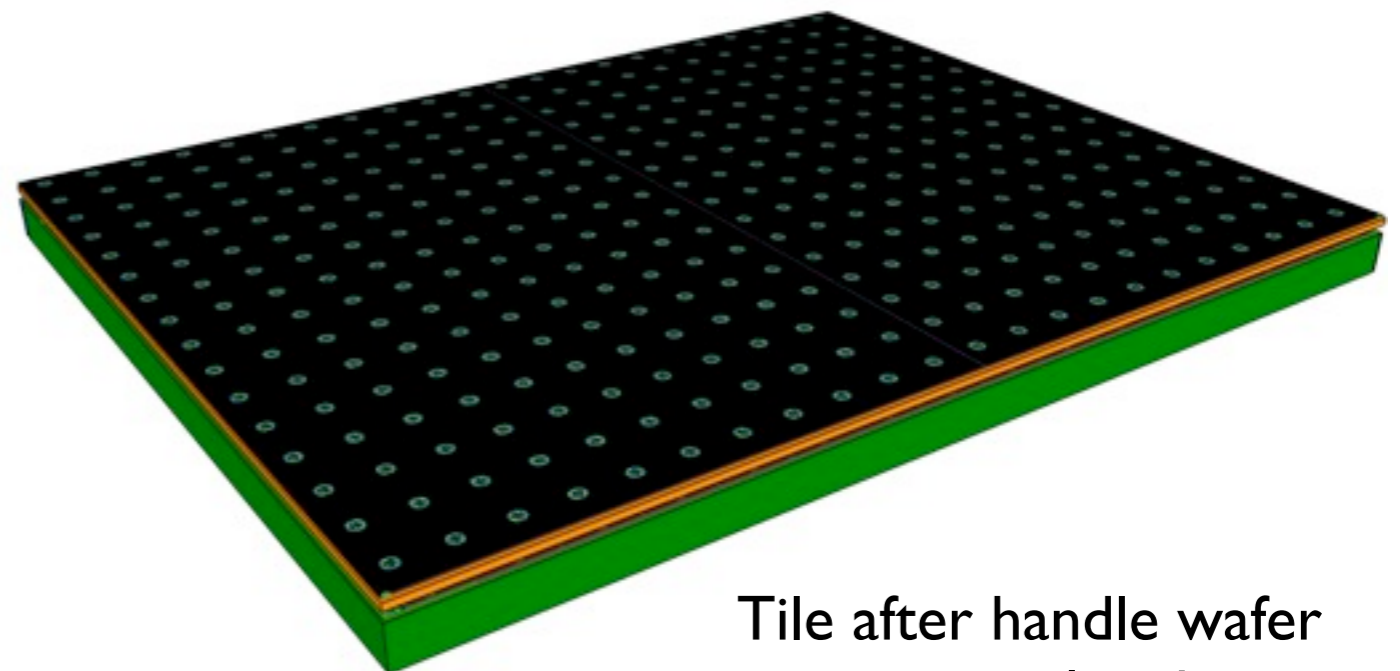
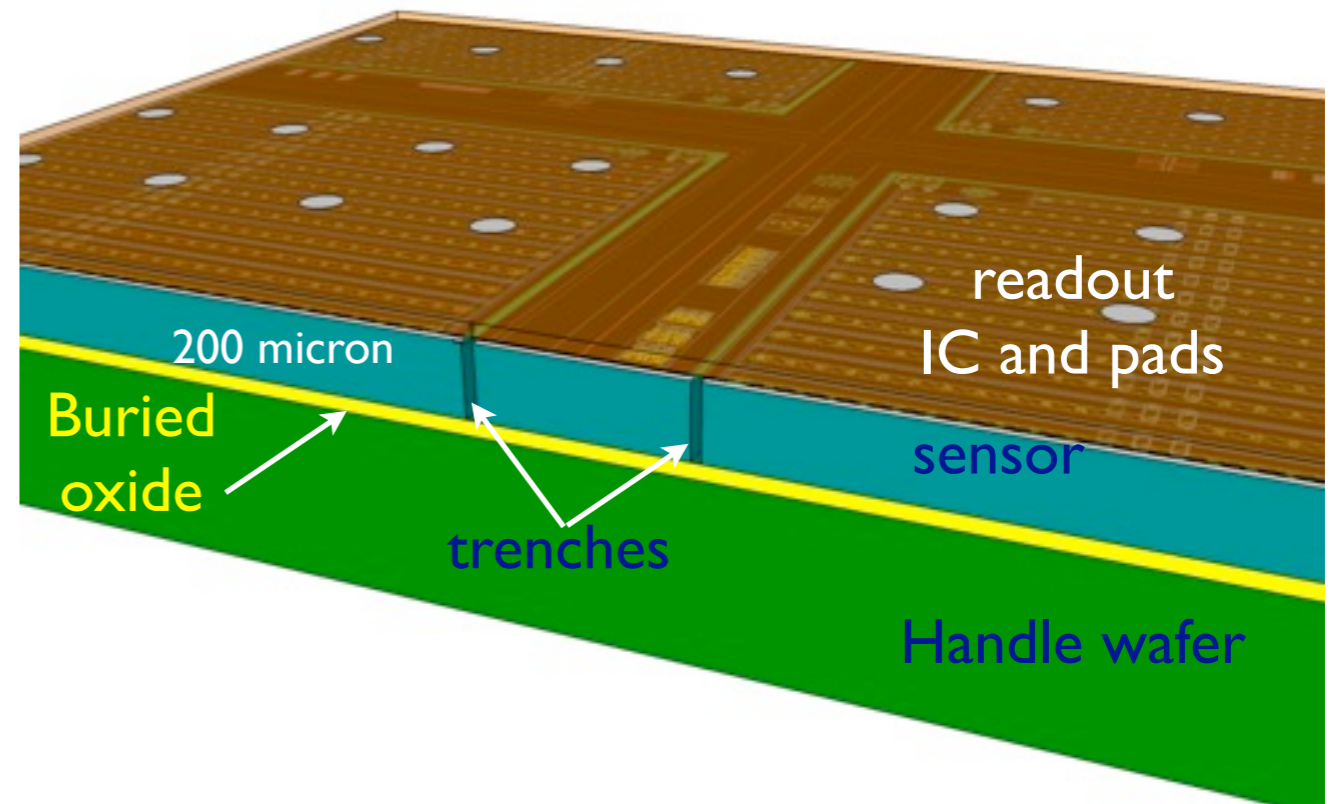
The goal of “double 3D” work is to combine active edge technology with 3D electronics and oxide bonding with through-silicon-vias to produce fully active tiles.



- Driven by CMS track trigger needs (100's of m² of 3D pixelated sensors)
- These tiles can be used to build large area pixelated arrays with good yield and low cost because the only bump bonds are large pitch backside interconnects.
- Fine pitch bonds to the sensor are made using wafer to wafer oxide bonding
- The SOI-based technology can provide very thin sensors

Active edge assembly

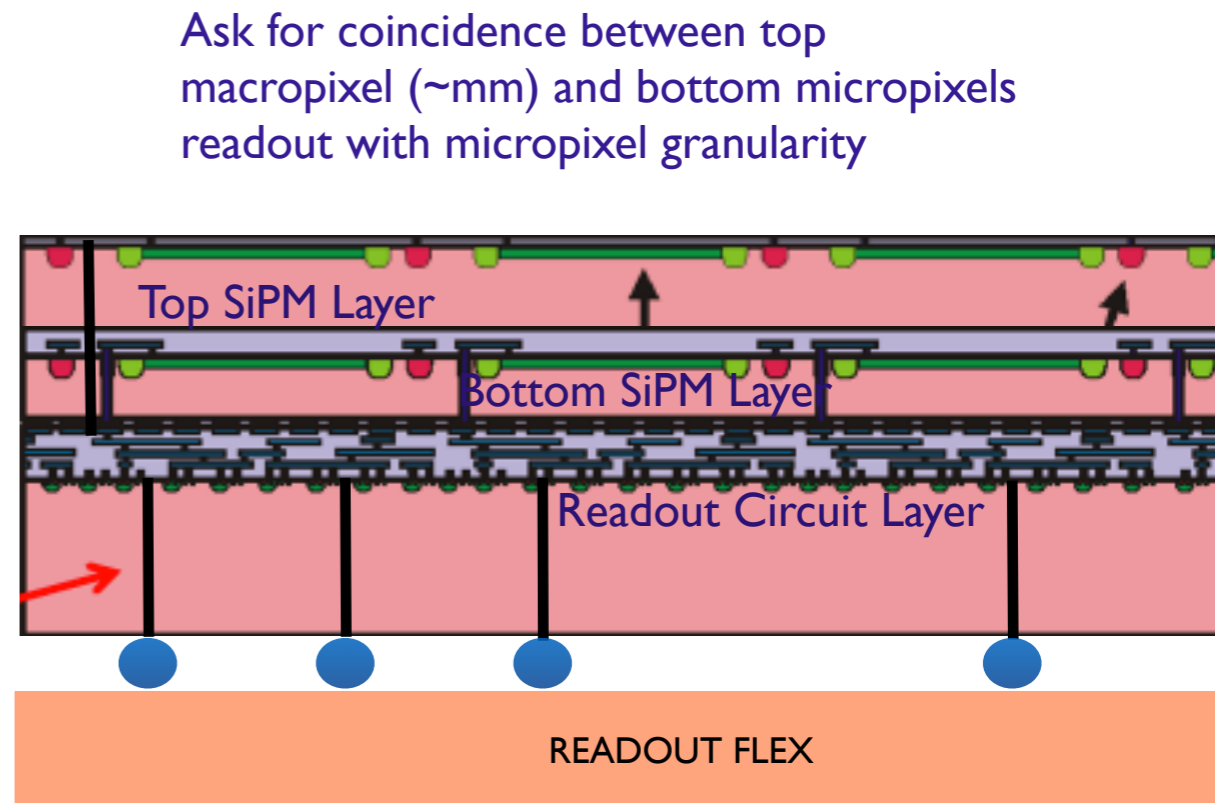
- As a final step the polysilicon in the trenches and the handle wafer have to be removed - this will be done at Stanford in collaboration with SLAC
- There are no trenches on the edge reticules to allow test of the UCSC/ NRL process



Tile after handle wafer
removal and
singulation

SiPM-Based 3D Tracking (Lipton)

- In a silicon strip or pixel detector much of the power is devoted to biasing the front-end transistor
- We can avoid this using avalanche effects in silicon (like gas)
- SiPMs could do this if the singles rates were not so high
- More than enough primary electrons in an SiPM thinned to 1-2 microns
- Reduce high “single photon” noise rates by a local coincidence
 - Ask for hits within a few ns in two adjacent layers
 - Use 3D integration to mate 2 SiPMs and ask for coincidence
 - Response could be very fast - <100 ps since all capacitances are low
 - Subpixel hit resolution ~15 microns
- **Very substantial power reduction**
- We have already proposed single layer 3D SiPMs as optical sensors with subpixel position resolution active subpixel quenching and improved time resolution.



Summary

- **We scratched the surface of tracking and detector technology for future project X experiments**
 - Most of the discussion was based on existing or near-future experiments -
 - Not enough time and effort to really understand the tradeoffs - and details matter
 - **We really need simulation of proposed geometries to understand requirements and tradeoffs**
- **Gas tracking is a well developed technology**
 - There is always room for innovation - multi anode straws
 - No discussion on pixelated gaseous tracking (micromegas, TPC, GEM,...) - could be strong candidates
- **Silicon leverages CMOS technology development. Candidate technologies exist for precise, low mass silicon tracking systems.**
 - Power is a major issue
 - New technologies may provide solutions (3D SiPM ...)